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(54) SURVEYING BODIES HAVING MAGNETIC AND/OR ELECTRIC FIELDS

(71) We, HOUSTON OIL & MINERALS CORPORATION, a Corporation orgnised and existing under the laws of the State of Texas, United States of America, of 1212 Main Street, Houston, Texas, 77002, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method and apparatus for determining the range to a target by measurement of magnetic and/or electric fields emanating from the body.

The methods and apparatus disclosed may be used in such diverse areas as the location of ore deposits, guidance systems for drilling off-vertical wells to intersect a previously drilled well, and locating metallic objects underwater.

The present invention finds particular application in the directional subsurface drilling of an off-vertical borehole using a magnetometer instrument to determine from the borehole the direction and range to a predetermined sub-surface target and provide information for guiding further drilling.

In drilling an oil or gas well, it is often desirable to drill the hole as nearly as possible in a true vertical course. Realizing that it is not possible to drill a well that is exactly vertical, at the conclusion of the drilling of the well it is routine practice to conduct a logging survey in order to determine the deviation from vertical of the well at various depths. In one case, the survey involves raising and lowering through the borehole an instrument that registers chances in its orientation from vertical using the earth's magnetic field and gravity as references. In another case, changes with respect to a gyroscopic reference are recorded. Suitable instruments for these purposes are well known to those skilled in art.

When a well "blows out", or goes out of control, it is desirable to intersect the main well with a relief well at a point above the high pressure producing formation in a suitably permeable zone, so as to allow fluid flow in order to plug the main well and eliminate the blowout. Such a relief well is drilled in order that cement or some similar material can be pumped down the relief well to kill the blowout. This course of action is particularly desirable in the case of wells having large flow rates, and particularly in the case of wells that have caught fire as well. Generally speaking, off-vertical well drilling to intersect a previously drilled well can be done fairly accurately if the location of the target is known with sufficient accuracy. However, due to the lack of accuracy in the logging of the off-vertical deviations of the first well, the exact position of the desired target point along the blow out well is generally not accurately known. Typically, the location will be known only to within about ten to forty feet. In view of the fact that the drill string being used to drill the off-vertical relief well cannot be turned on a sharp radius, and this must be set up directionally at a point far from the first well, it is difficult to precisely intersect the first well. Several attempts may be required to effect intersection. If, however, the target location along the first well site were able to be accurately pin-pointed, drilling could proceed more radily to intersection therewith. This, of course, is generally not the case.

Therefore, to expeditiously drill off-vertical relief wells to intersect a first well in order to shut off a well out of control, it is necessary to employ the technique of directional drilling. Directional drilling involves controlling the course of a

borehole by using surface and subsurface instruments to direct the drilling toward a specific target. Direction recording instruments are used to determine the desired direction of drilling with deflecting tools and/or directional methods being used down hole to control the downward course of the well.

One example of the use of direction recording instruments in off-vertical well drilling is a technique in which a magnetometer is located in a target well with a magnetic field generator, such as an electromagnet, being located in a second well some distance from the first. The electromagnet is carried by a drill string which is to be guided in accordance with the measurements of the field generated at the target well as obtained by the magnetometer. These measurements provide an indication of the direction of the generated field with the changes in the measured components providing an indication of the direction of travel of the drill with respect to the target magnetometer. This technique of off-vertical well drilling is taught in the prior art by U.S. Patents 3,285,350 and 3,406,766 to J. K. Henderson.

Another approach to directional drilling of off-vertical wells is that of U.S. Patent 3,725,777 to Robinson et al. The approach disclosed therein provides a method for locating a previously drilled well which is cased with a material having a remanent magnetization. Magnetometers measure the total strength of the existing magnetic field which is a combination of the field emanating from the magnetized casing plus the earth's field. Possible locations of the previously cased well are calculated; and assuming the strength and direction of the earth's field, the strength and direction of the field contributed by the cased well can be determined. The distance and direction to the cased well are determined by machine calculations involving a least squares fit analysis.

Another approach involving the determination of the distance between a cased well and a directional well is that of U.S. Patent 3,748,574 to Mitchell et al, which discloses a technique using resistivity measurements. In this technique, the expected resistivity of the formations surrounding the off-vertical well is determined in calculations made of the anticipated reduction in resistivity caused by the presence of the casing. A nomogram is prepared by plotting the calculated reduction versus the assumed distances for each calculated formation resistivity. The measured resistivity caused by the casing in the distance between the two wells is then obtained from the nomogram.

Generally, guidance systems for off-vertical well drilling will include subsurface magnetic field direction sensing devices and surface recording instruments for displaying the information concerning the magnetic field being sensed. The subsurface magnetic field direction sensing device is usually some type of magnetometer which detects the direction of emanation of the magnetic field of the target and of the earth, with the outputs therefrom being connected to the surface recording instruments.

Typically, the magnetic field direction sensing device will be a fluxgate magnetometer having a low reluctance magnetically directionally sensitive loop with drive coils and sense coils wound thereon. An oscillator produces AC current flow in the parallel drive coils which develops alternating magnetic forces in opposite directions in the loop. When the loop is not subject to any ambient magnetic field, the voltage induced in each sense coil will be equal and opposite, so that upon summing of the voltages no output is obtained. When the magnetic loop is subjected to an ambient magnetic field having lines of force including a vector component parallel to the loop, the balance between the sense coils is disturbed and an AC voltage is produced at the output. Since the magnetic field direction sensing device will be sensitive to the earth's magnetic field, some type of neutralizating technique is usually employed to adjust the flux being created in the loop to remove the influence of the earth's field and drive the output voltage of the sense coils to zero. Magnetometers of this type are sensitive only to magnetic fields perpendicular to the length of the loop.

In order to establish the direction of emanation of the magnetic field, it has been usual in prior magnetometer systems to utilize two mutually perpendicular fluxgate magnetometers defining X and Y coordinate vectors of the detected field. The vectors are generally resolved electronically and displayed on some type of surface recording instrument. Typically, the surface recording instrument will serve to resolve the vector components of the sensed magnetic field in a conventional manner using rectangular coordinates, as by plotting the component amplitudes and solving graphically for the actual field direction in the plane of the sensors. Representative of the foregoing described magnetic field sensing devices and magnetometer systems in Schad, U.S. Patent 3,731,752. In this reference, it is

further suggested that a third magnetometer could be used to measure X, Y and Z magnetic field components (Col. 4, line 55, et seq.).

Prior magnetometer guidance systems for off-vertical well drilling, such as that described above, generally position the magnetic field direction sensing device in an existing well that is to be intersected by a second well. Thus, the magnetometer becomes the target with the electromagnet, creating a detectable magnetic field. The requirement that a magnetic field generator be used to set up a detectable magnetic field can present insurmountable problems in those situations, such as a blowout well, wherein it is not possible to place a magnetometer device or a field generating source in the target well.

Thus, it is desirable to have a surveying system for guiding off-vertical well drilling which is capable of locating a subsurface ferromagnetic target such as a length of drill string, a drill tool or well casing in the target well. Such ferromagnetic material will demonstrate and possess remanent magnetization since most drill pipe and well casing is electromagnetically inspected before it is installed, leaving a residual magnetic field in the casing. Even were this not the case, the magnetic influence of the earth's field will induce some magnetization which may be detected in a ferromagnetic material in the target well.

In accordance with one aspect of the present invention there is provided a method of surveying to determine the range from a borehole to a subterranean target exhibiting a magnetic or electric field, comprising measuring the intensity of the magnetic or electric field at a plurality of locations along the length of the borehole to provide signals representative of the intensities at said locations and of the spacing of said locations; utilizing said signals to determine the gradient, in the direction of the borehole, of said field and to provide signals representative of the gradient; and utilizing said signals representative of the intensities and said signals representative of the gradient to determine the range to the target from one of said locations.

This method may be used to determine the range to a target having a static magnetic field, a time-varying magnetic field or an electric field, and the target may thus comprise an adjacent well having remanent magnetization, an adjacent well having a magnetic field set up around it by the flow of current through the well casing, or an adjacent well having an electric field emanating therefrom caused by the application of an electric potential to the well casing.

In preferred embodiments of the invention, not only the range but also the direction to the target are determined.

In the case of a target exhibiting a static magnetic field, e.g. a body having remanent magnetization, and therefore a static field, the determination of the direction to the target is made by measuring three magnetic field components, and resolving those components into a resultant vector in accordance with conventional vector analysis calculations. Range determination is made by measuring the total magnetic field intensity and the gradient, in the direction of the borehole, of the field of the target, and then using these measurements to determine the range. It is to be recognized that the total magnetic field will be a combination of the field emanating from the target plus the field of the earth.

The measurements of a component of magnetic field intensity and target field gradient are conveniently made using two axially displaced magnetic field sensors separated by a known distance. The average of the measurements of the sensors yields the measurements of component of magnetic field intensity over the separation Δr, between the sensors, and the difference, ΔH, in the readings of the two sensors divided by the distance of separation, Δr, yields $\Delta H/\Delta r$ which is the average magnetic field intensity gradient over the separation between the displaced sensors. Measurements are preferably made at a minimum of three locations along the borehole, thereby defining two separations over which average total magnetic field intensity and average target field intensity gradient measurements are made. Ratios of magnetic field intensity to target magnetic field intensity gradient are calculated for the two defined separations, using the corresponding values of magnetic field intensity and gradient determined for each of the defined separations. The calculated ratios are then substituted in an equation that is derived from the general expression relating magnetic field intensity of a body and the distance away from the body that an observation point is established. The general equation is $H = Kr^{-n}$, where K is a constant dependent upon properties of the magnetic body and n is the fall-off rate with distance r of the intensity of the magnetic disturbance, also dependent upon the particular characteristics of the target magnetic body.

In the situation where the target to be located exhibits a time-varying magnetic field, a slightly different approach must be employed in the surveying operation. A time-varying magnetic field set up about a subterranean magnetic body by virtue of an alternating current being applied to the body will result in a circularly distributed pattern of equal intensity points around the axis of the target magnetic body. By utilizing a magnetic field sensor that is designed to have a maximum response when aligned tangentially to the magnetic flux lines that follow a circular path and a minimum response when the sensor is aligned perpendicularly to the circular magnetic field lines; the direction to the target body may be determined by detecting the time-varying field set up around the target and determining the orientation of the sensor in which a minimum response is obtained, the direction of the axis of the sensor thus being the direction to the target. The range to the target magnetic body may be determined in accordance with the technique employed with respect to static magnetic fields but with appropriate modification in view of the direction of the field; however when phase-lock detection is employed using a sample of the current source as a reference, only a single magnetic field sensor need be used with measurements being made at a minimum of three locations along the borehole at known distances of separation.

In the situation where a target does not exhibit a detectable alternating magnetic field, but does have an alternating electric field existing about resulting from the application of an electric potential to the target, electric field probe sensors may be utilized to detect and measure the electric field gradient. Direction to the target is determined by adjusting the orientation of the instrument in which the electric field sensor is placed until the sensor shows a maximum voltage gradient, as when the electrode sensors are aligned in the direction of the target body. Range to the target electrically conductive body is made in a manner similar to that for the other two cases; however, electric field intensity and electric field gradient are used rather than magnetic field intensity and magnetic field intensity gradient.

In a further aspect, the present invention also provides a method of directional subsurface drilling of a borehole to intersect a subterranean target exhibiting a magnetic or electric field, comprising determining the range and direction to the target from the borehole by an appropriate surveying method of the invention; and orienting the direction of drilling of the borehole in the direction of the target from a position in the borehole from which the target may be conveniently intersected, based upon the target range and direction determinations.

This method may conveniently be used for drilling an off-vertical relief borehole to intersect an adjacent well, e.g. one that has blown out.

The present invention also provides apparatus suitable for carrying out the above methods and hence provides, in a further aspect, surveying apparatus for determining the range to a target exhibiting a magnetic or electric field, comprising first and second field sensors spaced apart by a predetermined distance along a reference axis, the sensors either being responsive to a static magnetic field or to an electric field and being arranged with their axes of maximum sensitivity aligned along said reference axis, or the sensors being responsive to a time varying magnetic field and being arranged with their axes of maximum sensitivity perpendicular to said reference axis.

The apparatus conveniently further includes surface data handling and data processing apparatus which comprises: circuitry for receiving output signals from the sensors and for conditioning and digitizing the received signal; a digital multiplexer circuit for routing the multiple channels of data onto a single data bus; and a programmable calculator connected to the data bus for receiving the digitized data. If time-varying electric fields are being detected, with the sensors providing A.C. output signals, the input circuitry would further comprise AC-to-DC converters disposed ahead of the signal conditioning amplifiers, or in the alternative, comprise synchronous detectors disposed ahead of the signal conditional amplifiers. Both the AC-to-DC converter and the synchronous detector convert the A.C. signals to a D.C. signal suitable for conditioning and digitizing. As an alternative to digital processing, the sensor output signals, after conditioning, may be applied to a strip chart recorder and/or a digital voltmeter.

A preferred embodiment of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIGURE 1 is a perspective schematic diagram of subsurface field sensing apparatus in accordance with the present invention in a borehole adjacent a cased well that is desired to be intersected with the borehole;

FIGURE 2 is a diagram relating to the "ranging" technique and illustrating the discussion associated therewith;

FIGURES 3 and 4 are diagrams illustrating the pattern of the magnetic field emanating from the cased well in Figure 1;

FIGURE 5 is a diagram of the coordinate axis system defined by the set of orthogonal magnetic field sensors carried by the subsurface field sensing apparatus of Figure 1 when disposed in an open borehole;

FIGURE 6 is a vector diagram relating to the development of correction factors to be used in connection with the calculation of borehole elevation and azimuth correction angles;

FIGURE 7 is a cross-sectional view of the subsurface field sensing apparatus of Figure 1;

FIGURE 8 is a block diagram of the subsurface electronics carried by the subsurface field sensing apparatus of Figure 1;

FIGURE 9 is a schematic representation of the response pattern of the magnetic sensor elements of the apparatus of Figure 1;

FIGURE 10 is a diagram of the arrangement of the magnetic sensors within the subsurface magnetic field sensing apparatus of Figure 1, as depicted by the response patterns of the sensors;

FIGURE 11 is a schematic diagram of a suitable oscillator circuit for use in the subsurface electronics block diagramed in Figure 8;

FIGURE 12 is a schematic diagram of the circuitry for one of the magnetic field sensors of the apparatus of Figure 1;

FIGURE 13 is a perspective diagram of a magnetic sensor core element suitable for use in conjunction with the magnetic field sensor circuitry of Figure 12;

FIGURE 14 is a side view of the sensor core element of Figure 13 with its response pattern representation imposed thereon;

FIGURE 15 illustrates the signals to be expected from the output terminals of the sensor core element of Figures 13 and 14;

FIGURE 16 is a schematic diagram of the electronic circuitry for time-varying magnetic and electric field sensors in the subsurface field sensing apparatus of Figure 7;

FIGURE 17 is a schematic diagram of a voltage regulator suitable for the regulation of the subsurface power supply voltages;

FIGURE 18 is an illustrative diagram of a suitable embodiment for the vertical sensor shown in the block diagram of Figure 8;

FIGURE 18A is a plot of the output response of the vertical sensor device of Figure 18; and

FIGURE 19 is a block diagram of the surface instrumentation that received the data acquired by the subsurface instrument of Figure 1.

A. GENERAL THEORY

The general theory upon which the method and apparatus of the present invention are based is that generally descriptive of and applicable to magnetic and electric fields. The principal focus of the present invention is, however, on the utilization of magnetic fields existing about and emanating from a subsurface target source.

In certain embodiments the present invention utilizes the characteristics of the magnetic field of the earth and of a target magnetic source to provide information from which the target range and direction with respect to subsurface magnetic sensing apparatus can be determined. Orientation of the subsurface magnetic sensing apparatus located in the borehole being drilled is determined through referencing with respect to the earth's magnetic field, a known quantity both as to intensity and dip angle at a particular location on the earth.

Fig. 1 illustrates one application to which the methods and apparatus of the present invention can be applied, that application being the drilling of a directional relief well to intersect a previously drilled well.

1. Target Range.

Large pieces of magnetic material, such as magnetized casing or drill string in a borehole, can create anomalies in the earth's magnetic field. An anomaly of this sort will appear as a magnetic field of intensity H superimposed on the earth's magnetic field. The general form of the expression for the magnetic field as a function of distance from the anomaly is given by:

$$H = \frac{KM}{r^n} \qquad (1)$$

where K is a constant dependent upon such properties as magnetic susceptibility of the surrounding medium, M is the magnetic moment of the magnetic body, and n is the fall-off rate with distance, r, of the magnetic field intensity H of the body.

Differentiating the above expression yields the rate of change of the magnetic field intensity with respect to radial position from the center of the magnetic body. That derivative is:

$$dH/dr = \frac{-nKM}{r^{n+1}} \qquad (2)$$

and expresses a vector quantity that may be referred to as the gradient of H, or grad H, in the radial direction. By forming the ratio of H/dH, an expression results involving only the range, r, to the magnetic body and the fall-off rate n. That expression is:

$$\frac{H}{dH/dr} = \frac{(KM)}{(r^n)} \frac{(r^{n+1})}{(-nKM)} = \frac{-r}{n} \qquad (3)$$

If two measurements are made such that

$$\frac{H_1}{dH_1\text{-}dr} = \frac{-r_1}{n} \text{ and } \frac{H_2}{dH_2/dr} = \frac{-r_2}{n}$$

then upon division,

$$\frac{H_1}{H_2} \frac{(dH_2/dr)}{(dH_1/dr)} = \frac{r_1}{r_2} \qquad (4)$$

or in the alternate,

$$\frac{H_2}{H_1} \frac{(dH_1/dr)}{(dH_2/dr)} = \frac{r_2}{r_1}$$

This derivation indicates that the range, r, of an observation point in space from the magnetic body can be determined from measurements of the magnetic field intensity taken at three or more points along a substantially straight line intersecting the axis of the relief well to determine the average gradient of the magnetic field between those points.

The values of H and dH/dr for the above equations can be measured using two aligned magnetic field sensors spaced at a fixed distance apart. For greater accuracy, an average of the magnetic field intensities measured on two magnetic sensors can be used for the value of H. The difference ΔH in the readings between the two magnetic sensors divided by the separation Δr between them yields ΔH/Δr, which is the average gradient of the magnetic intensity H over the separation and a good approximation of dH/dr.

The diagram of Figure 2 illustrates the foregoing discussion. In order to obtain two measurements of H and dH/dr, for substitution in the above equations, it is necessary to name at least three measurements of the magnetic field intensity H. To obtain H_1, the magnetic field intensity at points a and b must be measured and averaged. The separation of the magnetic sensors defines points a and b, with Δr being the distance therebetween. The approximation of dH_1/dr is obtained by dividing the difference in the measured field intensities at points a and b, designated ΔH_1, by the separation Δr. To obtain H_2, the two magnetic sensors are each moved to a new location along the common axis, with the sensor previously at point a moving to point b and the sensor previously at point b moving to point c. Similar to the determination of H_1, the magnetic field intensity is measured at

points b and c with the value of H_2 being the average of the two measurements. The approximation of dH_2/dr is obtained by determining the difference between the intensities at points b and c, $\Delta H2$, and dividing that quantity by the separation Δr.

As can be seen in Figure 2, the values of r_1, and r_2 for substitution in equation (4) are:

$r_1 = r + 3\Delta r/2$ and

$r_2 = r + \Delta r/2$.

Measurements would be repeated at intervals as the sensors are advanced along a path to update and monitor the closing of the range. Ranging accuracy can be improved with the measurements being made at intervals that are closer together, approaching a continuous recording.

Substitution in equation (4) of the values of H and dH/dr determined as discussed above results in the following equation:

$$\frac{H_2(\Delta H_1/\Delta r)}{H_1(\Delta H_2/\Delta r)} = \frac{r + \Delta r/2}{r + 3\Delta r/2} \tag{5}$$

which can be simplified to

$$\frac{H_2\Delta H_1}{H_1\Delta H_2} = \frac{r + \Delta r/2}{r = 3\Delta r/2} \tag{6}$$

and rewritten to express the range, r, as follows:

$$r = \frac{\dfrac{3\Delta r H_2 \Delta H_1}{2H_1\Delta H_2} - \dfrac{\Delta r}{2}}{1 - \dfrac{H_2\Delta H_1}{H_1\Delta H_2}} \tag{7}$$

If

$$\frac{\Delta r}{2}$$

is insignificant when compared to r, by deleting the second term of the top line the equation reduces to:

$$r = \frac{1.5\Delta r}{\left(\dfrac{H_1\Delta H_2}{H_2\Delta H_1} - 1\right)}, \tag{8}$$

where

$$H_1 = (Hb + Ha)/2;\ H_2 = (Hc + Hb)/2$$

$$\Delta H_1 = H_b - H_a;\ \Delta H_2 = H_c - H_b$$

The range r will be expressed in the same dimensions as those with which the separation Δr is measured. Typically, it would be in feet or meters.

Once the range r is determined, the fall-off rate n may be ascertained to indicate the character of the magnetic target. The value of n is obtained by solving the equation obtained from equation (3)

$$n = \frac{-r.(dH/dr)}{H},$$

or the approximation formula

$$n = \frac{-r.(\Delta H_1/\Delta r)}{H_1}$$

It is to be appreciated that the ranging technique described above can also be carried out with a single magnetic sensor. If only one sensor is used, the measurements of magnetic field intensity must be correlated with the distance from the magnetic body, e.g. the distance down a borehole, (the Δr distance) at which they are taken in order to ascertain the separation between the points at which the measurements are made. This can be done, e.g. by suspending the sensor down a borehole with a cable that is marked to indicate its length. The separation is required to permit the average gradient of the magnetic field, $\Delta H/\Delta r$, to be determined.

It is to be pointed out that because of practical considerations ranging with a single magnetic sensor will not be as accurate as with two sensors of fixed separation. Most important of the practical limitations on using one sensor is the difficulty of ensuring that the sensor is similarly oriented at each of the measurement locations. It is a basic premise of the ranging technique that the field intensity measurements be made along a straight line intersecting the magnetic body and that the orientation of the magnetic field sensor (s) is the same at each measurement location.

2. Target Direction.

Magnetized structures of various dimensions and configurations create magnetic fields having a characteristic emanation pattern. For example, a magnetized elongate structure forming a magnetic dipole will have magnetic flux lines emanating from one end to the other. However, if the structure is sufficiently long and the point of observation is moved proximate one end, the magnetic field will appear to be one emanating from an endless linear magnetic source in the form of outwardly, radially directed flux lines extending from the elongate magnetic structure. The magnetic field characteristics can be utilized through appropriate detection by magnetic field sensors, with proper interpretation of the measurements and knowledge of the earth's field, to determine direction to the magnetic body from some point in space.

The usual situation confronted in directional subsurface drilling is that in which a well casing or a length of drill string is the magnetic body to be detected, as in Fig. 1. With the elongate configuration creating a dipole and with the observation point in space being located at a distant point far away from the structure, the magnetic field emanating therefrom will appear to be a radially directed field, as illustrated in Fig. 3 and Fig. 4, with an intensity given by $H = KM/r^2$. Utilizing a set of three magnetic sensors arranged orthogonally, the earth's magnetic field and the target's field can be detected and expressed as three components. Since the earth's magnetic field is of a known intensity and direction, its contrubution in the readings of the three sensors can be subtracted out, leaving only the component values of the target's magnetic field in the coordinate system defined by the orthogonal magnetic sensors. The component values can be resolved using conventional vector-analysis techniques to yield an indication of the direction to the target magnetic body.

Referring to Fig. 5, there is an illustrative diagram of a magnetic target and the coordinate system defined by magnetic sensing apparatus adequate to serve as an example to which the theory and approach to determining target direction can be applied. The coordinate axis system defined by the three orthogonal magnetic sensors has its three axes referenced as X', Y' and Z'. The horizontal X' axis and the slanted off-vertical Y' axis are perpendicular to the axis of the borehole which is the Z' axis. Due to the slant δ of the borehole, the coordinate axis system formed by the orthogonal magnetic sensors has rotated about the X' axis; and while having a common origin, the magnetic sensor coordinate system and the surface coordinate system XYZ do not coincide.

The magnetic field sensors associated with the X', Y' and Z' axes will measure

the magnetic field intensity components of the total magnetic field (i.e. earth and target). The measured component magnetic field intensitites of the target field will be referred to as H_x', H_y', and H_z'. The diagram of Fig. 5 will also serve as a vector diagram with the reference designations H_x', H_y' and H_z' indicating relative magnetic field components attributable to the target magnetic body.

With the magnetic sensors still a significant distance from the target such that there is no contribution by the target's magnetic field to the measured component values, the earth's magnetic field components in the X', Y', Z' coordinate axis system can be determined. While the earth's field does have a gradient, it is so slight as to be regarded as insignificant and its intensity treated as a constant. As the field of the target becomes measurable with the advancement of the magnetic sensors down the offset borehole, the measured earth's field components can be subtracted from the total field components being detected by the sensors, thereby leaving only the components due to the target's field in the X', Y', Z' coordinate system.

Knowing the components of the target field, the location of the target with respect to the origin of the X', Y', Z' coordinate system can be determined.

A complete description of the components of the earth's magnetic field, H_e, in the axial and radial directions can be calculated for any depth location of the magnetic sensors in the subsurface borehole. In order to formulate this description, knowledge is required of the total field intensity, H^T, and the dip angle, Φ, of the earth's magnetic field at the specific location on the earth where the borehole is to be drilled. The total field intensity and dip angle can be obtained from the U.S. Navy Hydrographics Office.

It is also necessary to know the angle of inclination, σ, from horizontal and the direction, θ, from magnetic north, at the various depths of interest, of the borehole. This information is obtained prior by taking magnetic field measurements with the subsurface magnetic sensing apparatus. Alternatively, a determination of borehole direction and deviation from vertical, referred to as inclination, at various depths is obtainable through a survey conducted by a photoclinometer or clinograph. Both instruments record a series of deviation measurements correlated with their depth on one trip into and out of the borehole. From either, it is possible to determine the course and direction of the borehole.

With the above information, the component values of the total field, H_T, is in the X', Y', Z' coordinate axis system can be expressed by the equations:

$$H_x' = H_T \cos\phi \sin\theta$$

$$H_y' = H_T [\sin\phi \sin\sigma + \cos\phi \cos\theta \cos\sigma]$$

$$H_z' = H_T [\sin\phi \cos\sigma - \phi \cos\theta \sin\sigma].$$

The predicted values of the earth's magnetic field in the X, Y, Z coordinate system may be used to check out proper operation of the magnetic sensors. Also, deviations from the predicted values can be used to indicate the presence of a magnetic target.

To illustrate the above equations, assume that the earth's field, H_e, is 43,168 gammas and the dip angle is 37.6 degrees. Further assume that the borehole direction is 33.5 degrees and the borehole inclination is 38.9 degrees. From the above equations, with $H_T = H_e$, the earth's field component along the X' axis is 18,877 gammas. The component along the Y' axis is 38,736 gammas, and the component along the Z' axis is 2575 gammas. To check the values, they may be resolved into a resultant according to the mathematic expression — $\sqrt{H_x^2 + H_y^2 + H_z^2} = H_T$. Substituting the above values yields the earth's field of 43,168 gammas, as it should.

Continuing with reference to the diagram of Fig. 5, from the magnetic field intensity component H_x', H_y' and H_z' measured by the orthogonal magnetic sensors, the azimuth correction angle θ_c and the elevation angle σ_c can be determined. Assuming no rotation of the coordinate axis system about the Z' axis, the azimuth correction angle θ_c can be determined as:

$$\tan\theta_c = \frac{H_x'}{H_z'}$$

$$\theta_c = \tan^{-1} \frac{H_x'}{H_z'}$$

The elevation correction angle σ_c can be determined as:

$$\tan \sigma_c = \frac{H_y'}{H_x'^2 + H_z'^2}$$

$$\sigma_c = \tan^{-1} \frac{H_y'}{H_x'^2 + H_z'^2}$$

If rotation of the X', Y', Z' coordinate axis system occurs, there will be no change in H_z'; however, the values of H_x' and H_y' will be affected. The vector diagram of Fig. 6 illustrates the following calculations which provide corrected values for the component values, H_x' and H_y'. The corrected values are used in the above equations for the azimuth correction angle θ_c and the elevation correction value σ_c. In the diagram and calculations, ϕ represents the angle of rotation of the coordinate axis system. From the diagram and beginning with the expression

$$Hy = \frac{H_y'}{\cos \phi} + H_x \quad \tan \phi,$$

which can be rewritten as

$$H_y = \frac{H_y'}{\cos \phi} + H_x \frac{\sin \phi}{\cos \phi}$$

and simplified to

$$H_y \cos \phi = H_y' + H_x \sin \phi,$$

from which it can be shown that the corrected value is

$$H_y' = H_y \cos \phi - H_x \sin \phi.$$

Further, it can be readily appreciated that

$$H_x' = H_y \sin \phi + H_x \cos \phi.$$

The resultant, R, in the vector diagram of Fig. 5 should not be confused with the range, r, determined in accordance with the ranging technique previously described. The resultant, R, relates only to the directionality of the detected magnetic target, and its magnitude is merely indicative of the total target field strength. The value of the field can be calculated according to:

$$H \text{ target} = \sqrt{H_x'^2 + H_y'^2 + H_z'^2}.$$

The foregoing discussion of target direction determination has been with respect to the detection of static magnetic fields; however, an alternative approach may be used if a time varying magnetic field can be set up about the target. In order to set up a time varying magnetic field, a well casing or the like is excited with an A.C. current. The field resulting from this type of excitation will, if diagramed appear as a series of concentric rings emanting from the target source. The circular flux of the field will be directed in accordance with the familiar "right-hand rule". The intensity of field produced will fall-off at a rate inversely proportional to the distance from the source, i.e. $H = KI/_r$.

An A.C. magnetic field sensor having a sensitivity response that is a maximum along one axis, when aligned with the field, and a null along another axis perpendicular to the maximum sensitivity axis, when aligned with the field, is

suitable to detect the time varying magnetic field and be used to indicate direction to the target. Placed in the time varying field described above, a maximum signal would be detected with the first axis defined above oriented tangentially to the circular flux lines, and a minimum would be detected with the sensor oriented with the null axis tangential to the circular lines.

Therefore, with the A.C. magnetic sensor in the time-varying magnetic field set up around the target casing, direction to the target can be determined by changing the orientation of the sensor until a null response is obtained. Knowing that a null response will occur only when the maximum sensitivity axis is perpendicular to the circular flux lines emanating from the target sources, the direction to the target will be that direction in which the maximum sensitivity axis is pointing.

The time-varying magnetic fields produced by alternating electric currents injected into the target well casing can be utilized in the same manner as described above and will have additional advantages of synchronous detection and the elimination of the effects of the Earth's magnetic field, thereby increasing the precision of the survey.

B. SURVEYING APPARATUS.

Surveying apparatus in accordance with the present invention for implementing the above theory and techniques for determining the range and possibly also direction from a borehole to a subterranean target conveniently includes both surface and subsurface instruments.

The subsurface instrument comprises appropriate electric or magnetic field sensors, e.g. magnetic sensors and associated operating circuitry which provide a highly sensitive magnetometer capable of detecting minute magnetic fields, the sensors being appropriately arranged to permit the ranging technique described above to be carried out. The subsurface instrument preferably also comprises suitable components to enable determination of the direction to a subterranean target as described above, e.g. three magnetic field sensors arranged to measure three mutually perpendicular magnetic field components.

The surface instrument comprises data processing equipment necessary for manipulating the data obtained by the subsurface magnetic field sensing apparatus. A programable calculator may be provided in which the conditioned data is sorted and subsequently processed. The data is processed in accordance with predetermined programs that manipulate the data to calculate range, and also direction in appropriate cases, to the predetermined subsurface target. Peripheral equipment may also provide for data storage and printout of the processed information.

The programs utilized to process the field intensity information being supplied from the subsurface instrument primarily carry out the calculations for target range and possibly also target direction determination. However, additional programs can be provided if desired to apply correction factors to the data being obtained to provide greater accuracy.

Though optional, the surface instrument may further comprise a strip chart recorder and various meters for displaying the data obtained from the subsurface instrument.

1. Subsurface Field Sensing Apparatus.

a. General

In preferred embodiments, the subsurface instrument is designed to detect both quasi-static and time-varying fields and to be capable of determining both the range and direction to targets exhibiting such fields. To provide such capability, the instrument includes multiple sensors to provide a D.C. magnetic field sensing system and an A.C. field sensing system. When static magnetic fields are to be detected, referred to as the passive mode of operation, the instrument's D.C. magnetic field sensing system is utilized. However, when operating in the active mode, as when time-varying fields are to be detected, the A.C. field sensing system of the instrument can be used.

The D.C. magnetic field sensing system for determining both range and direction to a target comprises a set of three mutually perpendicular D.C. magnetic field sensors defining an X'—Y'—Z' coordinate system. The X'-axis magnetic sensor and the Y'-axis magnetic sensor each comprise a single magnetometer; the Z'-axis magnetic sensor comprises two D.C. magnetometers that are spaced apart a predetermined distance. The orthogonal set of D.C. magnetometers are used to

determine the direction of the subsurface target from the subsurface instrument by measuring three magnetic field intensity components of the magnetic field emanating from the subsurface target. The magnetic field intensity components are those that are measured along the X′, Y′ and Z′-axes of the coordinate system defined by the orthogonal set of magnetic sensors. With this arrangement of magnetic sensors, the surface data processing instrument can calculate the direction of the detected subsurface target by resolving the magnetic field components into a resultant vector. The primary use of the two separated magnetometers that are aligned along the Z′-axis is to carry out the "ranging" technique previously described herein to determine the distance from the subsurface instrument to the detected subsurface magnetic target.

The A.C. field sensing system comprises two types of sensors. One sensor is an A.C. magnetic field sensor, and the other sensor is an electric field sensor. In order to use the A.C. field sensing system, a time-varying field, either magnetic or electric, must be set up around the target well. Typically, a high current cathodic protection type power supply attached to the well casing being used as a target is suitable. The power return may be made through any other grounding connection, such as a second well casing located some distance from the target casing.

Excitation of the target casing by current flowing along the casing produces a circular magnetic field around the axis of the target well casing. The A.C. magnetic field sensor can be used to detect the A.C. component of this field and determine directionality to the target. If it proves to be difficult to establish adequate current flow through the target casing to produce a satisfactory magnetic field, as when excessive current leakage to ground exists, the electric field probes may be utilized to detect the electric field gradient set up by the A.C. component of the excitation current.

b. Mechanical Configuration

Referring now to Figs. 7A and 7B, there is shown a cross-sectional view of one embodiment of a subsurface field sensing apparatus, referred to as apparatus 100, having a generally cylindrical and elongate configuration. The body portion of the apparatus comprises a tubular outer housing 102 of non-magnetic material, preferably stainless steel, having a nose cone 104 at the anterior and a connector housing 106 at the posterior. Nose cone 104 includes an adaptor 108 having threads 110 thereon which provide a means of attaching nose cone 104 to housing 102. Enclosed within the fiberglass nonconductive nose cone 104 are electric field probes 112 and an A.C. magnetic field pickup coil 114. Both the coil 114 for the A.C. magnetic field sensor and the electrodes for the A.C. potential detector are potted into nose cone 104. Wiring from coil 114 and electrodes 112 is also potted up through the nose cone 104 and connected to a terminal strip (not shown) at the rear of the nose cone.

Enclosed within the outer housing 102 are the electronics for subsurface apparatus 100. The various printed circuit boards containing the electronics for the various field sensing devices are carried on a frame 116 comprised of four elongate stringers 117 that extend substantially the entire length of the outer housing 102. The frame 116 further comprises a front bulkhead 118 and a connector bulkhead 120 between which the stringers are secured. A series of separating bulkheads, all referenced by the numeral 122, provide support to the stringers intermediate their ends.

The arrangement of the electronics within outer housing 102 has a Z′-axis sensor 124, referred to as the Z_1'-axis sensor, and its corresponding printed circuit board 126 disposed at the front of tool 100. A second Z′-axis sensor 128, referred to as the Z_2'-axis sensor, is disposed adjacent the connector bulkhead 120. A printed circuit board 130 disposed slightly ahead of the Z′-axis sensor 128 carries the electronics for that sensor. The separation between the Z_1'-axis sensor and the Z_2'-axis sensor is a predetermined and accurately fixed distance which is preferably approximately three feet. The X′-axis sensor 132 and the Y′-axis sensor 134 are disposed at a position intermediate the ends of the apparatus 100. A printed circuit board 136 positioned between the X′-axis sensor and the Y′-axis sensor carries the electronics for both sensors.

Disposed immediately behind the Y′-axis sensor 134 is the power regulator circuit board 137. Slightly further back and adjacent to the Z_2'-axis sensor electronics is the vertical reference sensor 138.

The mechanical positioning of the magnetic sensors is critical not only with respect to the outer housing 102 but also with respect to the other sensors. Proper

arrangement of the sensors will have the axis of maximum sensitivity for the Z_1'-axis sensor 124 and the axis of maximum sensitivity for the Z_2'-axis sensor 128 aligned with the longitudinal centerline axis of the outer housing 102. The axes of maximum sensitivity for the X'-axis sensor 134 and the Y'-axis sensor 132 will both be perpendicular to the longitudinal center-line axis of the housing 102. In addition, the axis of maximum sensitivity of those two sensors must be perpendicular to one another. Therefore, close attention must be paid to the mechanical alignment of the magnetic sensors of the subsurface field sensing apparatus.

Electrical power being supplied to the apparatus 100 from the surface power supplies, as well as the output signals of the various sensors with the apparatus 100, are carried over interconnecting wires 140 connecting to a cable connector 142 having connector pins 144. The cable from which the apparatus 100 is suspended during the surveying operations attaches to connector housing 106 by the internal threads 146 formed on the inside of the connector housing. The wires that extend between the subsurface apparatus and the surface instruments that records the measured data connect to connector pins 144 through a mating female connector (not shown).

c. Subsurface Electronics.

Referring next to Fig. 8, a block diagram of the electronics for the subsurface field sensing apparatus is presented. The electronics include the circuitry necessary for both the D.C. magnetic field sensing system, generally designated by the reference numeral 160, and also for the A.C. field sensing system, generally designated by the reference numeral 170. In addition, electronic circuitry is provided for maintaining proper power levels to the circuitry in both systems.

Referring first to the D.C. magnetic field sensing system 160, that system includes the four D.C. magnetometers 124, 132, 134 and 128 referred to previously in connection with Fig. 7. The magnetometers each produce an output signal that is proportional in amplitude and polarity to the magnitude and direction of the particular magnetic field intensity component that each is oriented to detect. The output signals from these magnetometers represent the X', Y' and Z' coordinate vectors from which may be resolved a resultant vector indicative of the total detected external magnetic field and the direction to the target magnetic source. In addition, the axial D.C. magnetic sensors 124 and 128 are used to make measurements of the Z'-axis component of the detected field at two separated locations along the borehole. From the measurements obtained, the target range can be calculated in accordance with the ranging technique described herein.

The D.C. magnetic field sensing system includes, in addition to the four D.C. magnetometers, an oscillator 180 which provides at its output an alternating excitation current of a predetermined frequency and magnitude. The oscillator output signal is introduced simultaneously to the core drivers of each D.C. magnetometer. The core driver amplifies the excitation current and supplies that amplified signal to a sensor core element which is driven into saturation by alternating the driving polarity at the frequency of the oscillator.

The sensor cores produce an output signal that is proportional in amplitude and polarity to the magnitude and direction of the magnetic field intensity component along the particular coordinate axis that the core is oriented to detect. Output signals from the cores, having the form of alternating positive and negative pulses, represent the X', Y' and Z' component vectors of the detected magnetic field. Returning to the block diagram of Fig. 8, the sensor output signal is introduced into a detector which respectively rectifies positive and negative pulses, differentially, integrating each, then adding the two quasi-static voltages summed. The output signal from the detector is fed to a servo driver from which a feedback signal is introduced into the sensor core secondary winding to provide a means of magnetically nulling out signal level errors introduced through temperature drift and offset voltage in the various amplifiers and extraneous magnetic flux in the core. The servo driver output is also connected to an output amplifier which increases the power level of the signal for transmission of the signal over the lengthy cables extending to the surface instrument.

Referring next to the A.C. field sensing system 170, the same includes electric field probes 172 for detecting the presence of an electric field. The electric field probes 172 are connected to an amplifier 174 which amplifies the developed electrical signal and passes it on to a frequency selective amplifier 176. The frequency selective amplifier 176 removes all extraneous noise, leaving only the information carrying signal. The signal is then, of course, available as an output for

transmission over its connecting cable to the surface instrument.

The second type of sensor in the A.C. field sensing system is the A.C. magnetic sensor 178. This sensor is responsive to time varying magnetic fields set up around a target source and produces an output signal functionally related to the detected field. The output signal from the A.C. magnetic sensor 178 is received by an amplifier 179 for amplification and conditioning prior to transmission to the surface instrument.

Prior to proceeding with a discussion of the circuitry of each D.C. magnetometer, special attention should be devoted to the magnetic sensor cores. Of particular interest is the magnetic sensor response pattern that is diagrammed in Fig. 9. The response pattern can best be described as being shaped like two spheres joined together. An axis of rotation, M, can be defined by a line segment passing through the point of contact of the spheres, S_1 and S_2, and also passing through the centers of both. Perpendicular to M and tangent to S_1 and S_2 at the point of contact is the null plane P. A second axis, referred to as a null axis N, may be defined that is perpendicular to and intersecting with the axis of rotation, M, which null axis lies in the null plane.

The output response of the magnetic sensor provides an output signal that in general substantially follows a cosine wave as the sensor core is rotated about the null axis N. Specifically, the magnetic sensor will produce maximum voltage output when the axis of rotation, M, which may also be termed the axis of maximum sensitivity, is aligned with the magnetic field. This may be more readily understood with reference to Fig. 9. Restated, the sensor output will be at maximum when the magnetic field being detected is directed as in H_1, that is $\omega = 0°$.

If the sensor is caused to rotate about the axis, M, the axis of maximum sensitivity, there will be no change in the sensor output. When the sensor is placed in a magnetic field that is directed at an angle oblique to the axis of maximum sensitivity, as is the field H_2, the sensor output will decrease as a function of cosine ω. Rotation of the sensor about an axis in the null plane with the magnetic field H_2 at a angle ω with respect that that axis will again not produce a change in the sensor output. If the angle ω is increased such that the magnetic field is directed normal to the axis of the maximum sensitivity, i.e. $\omega = 90°$, the sensor output will be zero. If the angle ω exceeds 90° such that the sensor is placed in a field directed as H_4, the sensor output will change from positive to negative, passing through zero.

In Fig. 10, there is presented a diagram of the subsurface apparatus 100 in which the D.C. magnetic sensors 124, 128, 132 and 134 are represented at their respective locations by their characteristic magnetic field sensitivity response pattern. As discussed previously, the magnetic sensors define a three-axis coordinate system, wherein the axes are designated X′ (horizontal), Y′ (vertical) and Z′ (axial). theoretically, the magnetic sensors should define coordinate axes that pass through a common origin; however, as a practical matter, this is not possible. But, it is to be appreciated that it is desirable to place X′-axis sensor 132 and Y′-axis sensor 134 as close to one another as is physically possible to approximate a common origin. The Z′-axis sensors 124 and 128 are, of course, separated by a defined distance Δr in order to carry out the ranging technique.

To be noted in the diagram of Fig. 10 is the fact that the axes of the coordinate axis system are defined by the axes of maximum sensitivity of the magnetic sensors. The axis of maximum sensitivity of both axial sensors 124 and 128 are aligned with the centerline of the apparatus 100. The centerline axis of the apparatus, of course, corresponds to the Z′-axis of the coordinate system. The horizontal and vertical axes are defined by the axes of maximum sensitivity of the sensors 132 and 134.

From the diagram of Fig. 10 and the discussion given above relating to the response pattern illustrated in Fig. 9, it will be apparent that the magnetic field emanating from a subsurface magnetic target source 151 will usually impinge each sensor core at a different angle ω because of the varying orientation of each sensor. This will cause a different output signal to be produced by each sensor. The output signal produced will be in accordance with the formula:

$$V_o = (K)\ (H) \cos \omega,$$

where

V_o = the sensor output;

H = the total magnetic field intensity;

K = a factor in volts/gamma expressing the voltage produced for a given field intensity; and

ω = the angle at which the magnetic flux lines impinge the sensor core.

It will further be apparent that, as the apparatus 100 is changed in orientation with respect to a magnetic field H_4, the output of the sensors will change in accordance with the above function. For example, as apparatus 100 rotates about the Y' axis, the axis of maximum sensitivity of the axial sensor 124 will become more nearly aligned with the field, resulting in an increased output signal from the sensor. However, as rotation occurs as described, the X'-axis sensor 132 will also be changing in orientation with the axis of maximum sensitivity therefor being turned away from the field. A change of orientation of the X'-axis sensor in this mannner will result in a decreasing output signal. It will be appreciated that rotation about the Y'-axis as described will have no effect upon the output of the Y'-axis sensor 134. The amplitude of the output signal therefrom will remain constant, as no change in the orientation of its axis of maximum sensitivity with respect to the field occurs. A change in the output of Y'-axis sensor 134 will, of course, be produced by rotation of apparatus 100 about the X'-axis.

In addition to the conductors for the output signals from the D.C. magnetometers of the D.C. field sensing system and the output signals from the A.C. field sensing system sensors, conductors must be provided for voltage regulator 150 which regulates the D.C. power provided by surface power supplies. Further included in the subsurface electronics is a vertical sensor 152 that provides information concerning the vertical orientation of the subsurface apparatus 100.

Specifically, the vertical sensor provides the angular relationship between the sensor reference plane that contains the axis M of the X'-axis sensor and vertical. Normal rotation in the borehole about the Z'-axis will move the X' and Y'-axes through random orientations and will provide instantaneous vertical and horizontal vector components of the detected field when their angular relationships with the vertical and horizontal planes are known.

Referring to Fig. 11, an oscillator circuit system 180 is presented. The oscillator circuit shown is commonly referred to as a Wien-bridge oscillator. The oscillator comprises an active element, operational amplifier 182, having a positive feedback network connecting to the non-inverting input and a negative feedback loop connecting to the inverting input. The negative feedback loop controls the gain of the amplifier and comprises resistors 184 and 186. The inverting input of operational amplifier 182 connects to the negative feedback loop at the junction of the resistors. The positive feedback network forms the second leg of the bridge and comprises two R—C networks. The first R—C network is comprised of resistor 188 and capacitor 190, which are arranged in series. The second R—C network is a parallel combination of resistor 192 and capacitor 194. The non-inverting input of operational amplifier 182 connects to the junction of the two R—C networks. As shown, both the positive feedback network and the negative feedback loop are grounded on one side and are connected to the output lead 196 of the operational amplifier through a feedback resistor 198.

The oscillator circuit 180 provides an amplitude-stabilized sine wave oscillator yielding a high purity sine wave output. Primarily, frequency stability depends upon the temperature stability of the components being used in the positive and negative feedback loops. In this particular application, the oscillator is preferably set up to provide a frequency of three kilohertz. Values for the components to provide this frequency are given in the Parts List at the end of the description of the electronics. To select a different frequency, reference may be had to the expression for frequency determination provided in the Linear Applications Handbook available from National Semiconductor at page AN 51—8.

Referring next to the circuit of Fig. 12, there is presented a schematic diagram for a D.C. magnetometer that is suitable for use in the D.C. magnetic field sensing system. The circuitry shown therein is representative of that which is used for each magnetic sensor 124, 132, 134, 128. As mentioned previously, the output of oscillator circuit 180 is applied to a core driver 200 which comprises a waveform shaping circuit and a push-pull emitter follower current amplifier. The oscillator output signal is applied to the core driver at terminal 201 and is passed to the waveform shaping circuitry by an A.C. coupling capacitor 202. The waveform shaping circuit has a gain that is slightly greater than one, preferably on the order of about 1.5. Since the amplitude of the oscillator output signal is at or very near the power supply limits, the gain provided in the waveform shaping circuit causes the sine wave from the oscillator to be clipped. After clipping, the waveform approximates a trapezoidal waveform.

The waveform shaping circuit is basically an inverting amplifier configuration utilizing an operational amplifier 204 and having a feedback loop consisting of

resistor 206 that connects between the output and the inverting input of operational amplifier 204. An input resistor 208 constitutes the input network and connects between the inverting input of operational amplifier 204 and coupling capacitor 202. The non-inverting input of amplifier 204 is connected to ground through a biasing resistor 210.

The push-pull emitter follower circuit is coupled to the waveform shaping circuit by a capacitor 212, and comprises an NPN transistor 214 and a PNP transistor 216 arranged in a conventional manner. The base of each transistor is connected to the coupling capacitor 212 through a resistor 218 or 220, respectively. A resistor 222 connects between coupling capacitor 212 and ground.

As will be readily appreciated, transistor 214 amplifies the positive portion of the near trapezoidal waveform from amplifier 204, and transistor 216 amplifies the negative portion of that waveform. The emitters of both transistor 214 and 216 are connected to a coupling capacitor 224 in series with resistor 226. Capacitor 224 couples the primary winding of sensor core 250 to the push-pull current amplifier of core driver 200.

Referring briefly to Fig. 13, a brief discussion of the sensor core 250 will be given to permit a more detailed understanding of the core, and also to provide adequate background for understanding the remaining portion of the D.C. magnetometer circuitry presented in Fig. 12.

The sensor core 250 is comprised of a toroid 254 and a bobbin 256 adapted to receive the toroid into a slot 258 formed in the bobbin. Toroid 254 is a tape wound core of 1 mil thick Supermalloy material, having a cross section measuring approximately 1/8" × 1/8". A winding 260 is placed on the toroid and used as the primary winding shown schematically in Fig. 12. Winding 260 preferably has approximately 150 turns of No. 32 wire.

The toroid bobbin 256, as shown is an I-shaped block of material having slot 258 formed vertically through the structure. A winding 262 is placed on the web portion of the structure, which winding constitutes the secondary winding represented schematically in Fig. 12. Preferably, winding 262 comprises 600 turns of No. 32 wire.

The diagram in Fig. 14 is a side view of sensor core 250 with toroid 254 inserted within the bobbin 256. The centerline axis, M, through the center of toroid 254 is the axis of maximum sensitivity, M. Also in dotted outline are two spheres, S_1 and S_2, which are used, as previously, to represent the response pattern of the magnetic sensors. Fig. 14 relates the physical configuration of the sensor core 250 to the response pattern diagram of Fig. 9.

Current injected into the primary winding 260 on toroid 254 produces a magnetic flux, whose direction is given by the familiar right-hand rule. Taking the toroid 254 in Fig. 13 and the clockwise winding of primary winding 260 thereon, flux is produced in the directions as indicated in Fig. 14. As shown, the flux in the left side of the core is directed upwardly, while the flux in the right side is directed oppositely to it. Core driver 200 supplies sufficient current to rapidly saturate the toroid core, causing the rate of change of magnetic flux in the core to approach zero. The secondary winding 262 is linked by the magnetic flux produced by the current in the primary coil. A change of this flux with time will induce a voltage in the secondary winding 262.

Referring briefly to Fig. 15, the waveform of the output voltage avilable from the secondary winding 262 at terminal 252 is illustrated. The output voltage is observed to be a series of alternately positive and negative-going spikes. During most of the period of each cycle of the driving signal, the net flux linking secondary winding 262 and the net rate of change of flux are zero because of the continuity of the toroid core that provides the magnetic path for the flux. During the instant that the left side and the right side are entering the region of saturation, however, spike is induced in the secondary winding due to the fact that both halves are not saturated at precisely the same time. When no external field component along the sensor axis (M) is present, the positive and negative spikes are equal in amplitude, as shown in Fig. 15a. When there is a component of external magnetic field along the sensor axis, the waveform appears as shown in Fig. 15b, wherein the positive spikes are greater in amplitude than the negative spikes. Circuitry is provided in the detector and servo-driver portion to compensate and balance the amplitudes of the pulses. That circuitry will be discussed when attention is again directed to Fig. 12.

With reference to the illustration of Fig. 14, wherein an external magnetic field H is aligned with the axis of bobbin 256, the magnetic flux in the right side of bobbin 256 will be greater than that in the other side. Assuming that the flux in the

right side is in the direction to produce a positive spike, the waveform of the output voltage will appear as the waveform illustrated in Fig. 15*b*. It will be appreciated that as the magnetic sensor core 250 changes in orientation with respect to an external magnetic field, such as that illustrated in Fig. 14, the component of the magnetic field aligned with the axis of maximum sensitivity will vary according to the cosine of the angle between the flux and the bobbin axis. This relationship was explained in detail in relation to the sensor response pattern of Fig. 9 in the discussion relating thereto.

Returning now to Fig. 12, the output signal from the sensor core 250 is applied to detector 300 through a coupling capacitor 302. Detector 300 comprises transistors 304 and 306 arranged in a push-pull configuration. Transistors 304, 306 have resistors 308 and 310, respectively, connected to their base leads, which resistors are in turn connected to coupling capacitor 302. A resistor 312 connects from the junction of the base resistors and the coupling capacitor 302 to ground. Transistor 304 detects the positive going spike of the output voltage, and transistor 306 detects the negative-going spike in the sensor output voltage waveform.

The positive spike from transistor 304 is applied to a balancing potentiometer 330 through a resistor and capacitor combination comprising resistor 314, resistor 316 and capacitor 318. This combination of components forms an integrator circuit and acts somewhat in the fashion of a peak-reading sample and hold circuit for the positive-going spike. In a similar fashion, the negative-going spike from transistor 306 is applied through a resistor and capacitor network comprised of resistor 320, resistor 322 and capacitor 324. The network also, in a manner of speaking, acts as a sample and hold circuit for the negative-going portion of the sensor output waveform.

As mentioned above, both the positive and negative portions of the sensor output voltage are applied to a potentiometer 330. Specifically, the two portions of the waveform are applied to opposite ends of the potentiometer with the wiper thereof being connected to the servo-driver 350. Potentiometer 330 through servo-driver 350 and the feedback line 360 associated therewith serves to drive current through the secondary winding 262 producing a magnetic feedback to balance out any imbalance between the amplitudes of the positive and negative spikes. Basically, the balancing is accomplished by adjusting the potentiometer 330 such that sufficient voltage is dropped across it on each side of the wiper to bring the amplitudes of the positive and negative spikes to the same level, reducing the error signal to zero. Should additional imbalance begin to occur, as by external magnetic field, the shift of relative spike amplitudes will result in a change in output signal amplitude and be fed back as a current to the output of the secondary winding of core 250 to create a field to compensate to the offset. Because the feedback arrangement maintains the operating point on the B—H loop of the magnetic core at the center of magnetizing force, and because the core is driven into saturation in both polarities, any change in permeability of the core due to temperature is balanced out exactly.

Servo-driver 350 is basically an amplifier circuit comprising an operational amplifier 352 driving a Darlington amplifier comprising of transistors 354 and 356 along with resistors 358 and 362. The Darlington amplifier provides significant current gain and input resistance with little increase in circuit complexity. The feedback path line 360 connects to the junction formed by the collector of transistor 354 and the emitter of transistor 356. Feedback line 360 includes a resistor 364 along with variable resistor 368. A filter capacitor 366 connects between the junction of resistors 364 and 368 to ground. The feedback line 360 extends between variable resistor 368 and terminal 252 of core secondary winding 262.

The gain for operational amplifier 352 is determined by the network connected between the servo-driver output lead at the collector of transistor 354 and the inverting input of operational amplifiers 352. Specifically, the gain is determined by resistors 370 and 372 with capacitor 374 being used to remove high frequency spikes, preventing their amplification and subsequent introduction into the feedback loop. Resistor 376 connecting between the inverting input of operational amplifier 352 and the junction of resistors 370 and 372 serves to match the input impedance between the inverting and non-inverting inputs of the operational amplifier 352. In order to provide an adjustment of offset in the servo-driver, the resistance network comprising resistors 378, 380 and potentiometer 382 is provided. The wiper of potentiometer 382 is connected through resistor 384 to the junction of resistors 370 and 372 to set a bias level at that point.

The output of the servo-driver is taken from the collector and emitter of the Darlington amplifier transistors and introduced into the output amplifier 400 through gain potentiometer 402 having a filter capacitor 404 arranged in parallel with it. In addition, a resistor 406 is placed in the circuit path ahead of potentiometer 402. Gain potentiometer 402 serves to adjust the level of the signal being introduced into the output amplifier. The gain adjustment potentiometer is preferably set to a point such that the output stage will operate without saturation when the magnetic sensor core is placed in an external magnetic field having an intensity as much as twice that of the earth's field. In addition to the gain potentiometer, the output amplifier 400 includes an operational amplifier 408 driving a push-pull emitter follower circuit, which circuit comprises transistors 410 and 412.

Resistors 414 and 416, respectively, connect to the base lead of transistors 410 and 412. The emitter follower circuit supplies the output signal through a resistor 418 to an output terminal 420. In addition, the feedback loop for the output amplifier 400 extends between the juction of the emitter leads of the transistors and the inverting input of 408. The network in the feed back loop comprises gain determining resistors 422 and 424 along with a filter capacitor 428 and impedance matching resistor 426. The output signal available from output amplifier 400 is of sufficient power level to transmit the signal over the cable that connects to the surface instrument.

The schematic diagrams for both the AC magnetic sensor circuity and the electric field probe circuitry are presented in Fig. 16. As shown, the AC magnetic sensor comprises a coil 450 in parallel with a tuning capacitor 452. The capacitor is used to tune the coil to the frequency of the time-varying magnetic field that is to be detected. The output of the magnetic sensor 178 is introduced to buffer amplifier 179 which is of a conventional configuration. Buffer amplifier 179 comprises an operational amplifier 454 having its non-inverting input connected to the AC magnetic sensor 178. A feedback loop extends between the output of the operational amplifier 454 and its inverting input, which feedback network comprises a parallel combination of resistor 456 and capacitor 458. In addition to the feedback loop, a resistor 460 also connects between the inverting input of operational amplifier 454 and ground. The output signal from buffer amplifier 179 is coupled to output terminal 462 through a coupling capacitor 464.

Turning now to the portion of the circuitry that provides electric field sensing capability, the electric field probes 172 are shown connected to the input circuitry of the buffer amplifier 174. Specifically, the electric field probes connect to a resistor 466 that is shunted across the input terminals 468 and 470 of buffer amplifier 174. One end of resistor 466 connects to ground, with the opposite end connecting to the non-inverting input of operational amplifier 472 Buffer amplifier 174 is of a conventional configuration having a feedback network extending between the operational amplifier output and its inverting input. The feedback loop comprises a parallel resistor and capacitor network consisting of capacitor 474 and resistor 476. In addition, a resistor 478 connects between the inverting input of operational amplifier 472 and ground. The output of buffer amplifier 174 is coupled to frequency selective amplifier 176 by a coupling capacitor 480.

Frequency selective amplifier 176 is an active filter utilizing an operational amplifier 482. A frequency determinative network connects to the inverting input of operational amplifier 482, which network determines the center frequency and the band width of the filter. The frequency determining network comprises a resistor 484 extending from the output of operational amplifier 482 directly to the inverting input thereof. In addition, a capacitor 486 connects to the inverting input of operational amplifier 482. An input resistor 488 connects between coupling capacitor 480 and the capacitor 486 with the junction of resistor 488, with capacitor 486 serving as the junction point to which the remaining components of the frequency determinative network connect. Capacitor 490 connects to the output of the operational amplifier 482 and shunts across resistor 484 and capacitor 486. Finally, a series connection of resistor 492 and potentiometer 494 connects to the junction of resistor 488 and capacitor 486. Potentiometer 494 is operative to adjust the center frequency of the band pass frequency selective filter 176. A biasing resistor 496 connects between the non-inverting input of operational amplifier 482 and ground. Finally, filter capacitors 498 and 499 connect to the positive voltage bus and the negative voltage bus, respectively.

Referring next to Fig. 17, a suitable voltage regulator circuit is shown for providing both regulated positive voltage and regulated negative voltage of

preferably about 8.5 volts each. Unregulated power from the surface power supply, both +12 volts power and −12 volts power, is supplied to the voltage regulator circuit 150 at terminals 501 and 502, respectively. The voltage regulator circuit 150 comprises an integrated circuit voltage regulator 504 for the positive voltage regulator portion, and a separate integrated circuit 506 for the negative voltage regulator.

Referring first to the positive voltage regulator circuitry, the +12 volts input voltage from the surface power supply is applied to the circuit 504. An NPN transistor 508 has its collector connected to the incoming power, and its base lead connected to the output terminal of the integrated circuit 504. The emitter of transistor 508 is connected to the inverting input terminal of circuit 504, which input is also connected to the wiper of potentiometer 510. A resistor 512 connects between one side of potentiometer 510 and the negative voltage input of circuit 504. Another resistor 514 conects between the opposite side of potentiometer 510 and the current sense terminal on circuit 504. A frequency compensation capacitor 516 is provided between the current limit terminal on circuit 504 and the frequency compensation terminal. In addition, a resistor 518 is placed between the current limit terminal and the current sense terminal on circuit 504. The regulated positive voltage output is taken at the junction of resistors 514 and 518, and is available from terminal 520.

Referring now to the negative voltage regulator portion, the voltage input to integrated circuit 506 is the regulated positive voltage available from the positive voltage regulator circuitry. The unregulated negative voltage being supplied to terminal 502 from the surface power supply is further applied to a Darlington amplifier circuit comprised of transistors 522 and 524, both PNP transistors, specifically, the negative voltage is applied to the collectors of the devices. A resistor 526 is placed between the joined collectors of the transistors and the base lead of transistor 522. The base of transistor 522 is connected to the integrated circuit 506, and the emitter lead of transistor 524 is connected through resistor 528 to the negative voltage terminal on circuit 506. In addition, the emitter of transistor 524 connects to a resistor network comprised of resistors of 530, 532 and potentiometer 534, which network provides output voltage adjustment. The resistor network, specifically resistor 532, is connected to ground, and the wiper of potentiometer 534 is connected to the non-inverting input of integrated circuit 506. A capacitor 536 connects between the frequency compensation terminal and the inverting input terminal of integrated circuit 506. The inverting input terminal is further connected to the reference voltage and negative voltage terminals of circuit 506 through resistors 538 and 540 respectively. The regulated negative voltage is available at terminal 542.

Additional information concerning positive and negative voltage regulators of the type described above may be obtained by reference to the Linear Integrated Circuits Data book of National Semiconductor, particularly pages 1—45 through 1-49.

PARTS LIST

Oscillator Circuit (180)

Resistors

184	4.7K
186	470Ω
188	4.7K
192	4.7K
198	10K

Capacitors

190	.01μfd
194	.01μfd

Amplifiers

182	LM 108	National Semiconductor

D.C. Magnetometer (124, 128, 132, 134)

Resistors

206	33K
208	22K
210	15K
218	1.0K
222	100K
226	1.5Ω
308	
310	
312	3.3K
314	100Ω
316	15K
320	100Ω
322	15K
330	50K
358	10K
362	1.5K
364	150Ω
368	2.0K
370	100K
372	1.0K
376	15K
378	120K
380	120K
382	50K
384	1.0Meg
402	100K
406	47K
414	1.0K
416	1.0K
418	100Ω
422	10K
424	2.0K
426	680Ω

Capacitors

202	.1 μfd
212	.1 μfd
224	.1 μfd
302	.1 μfd
318	.1 μfd
324	.1 μfd
366	.1 μfd
374	.01μfd
428	2.0 μfd
430	.1 μfd
432	22μfd
434	22μfd

Amplifiers

204	National Semiconductor
352	"
408	"

Transistors

214,216 MD6100	Motorola Complementary Pair
304,306 MD6100	"
354,356 MD6100	"
410,412 MD6100	"

A.C.Field Sensing System

Resistors

456	68K
460	1.0K
466	100K
476	68K
478	1.0K
484	68K
488	10K
492	270Ω
494	2.0K
496	220K

Capacitors

452	
458	1200pf
464	2.0 μfd
474	1200pf
480	2.0 μfd
486	.047μfd
490	.047μfd
498	22μfd
499	22μfd

Linear Circuits

454	LM108	National Semiconductor
472	LM108	"
482	LM108	"

Voltage Regulator (150)

Resistors

510	2.0K
512	6.8K
514	470Ω
518	5K
526	2.2K
528	2.2K
530	3.3K
532	4.7K
534	2.0K
538	2.7K
540	2.7K

Capacitors

516	100pf
536	100pf

Linear Circuits

504	LM723	National Semiconductor
506	LM723	"

Transistors		
508	2N3054	Motorola
522	MPS6523	"
524	2N3740	"

Referring to Fig. 18, there is illustrated one suitable device 550 that may be used for the vertical reference sensor 138. The vertical reference sensor has primary importance in providing information as to the orientation of the tool housing 102 with respect to a vertical plane. Having information concerning the rotational orientation of the tool 100 will permit increased accuracy in determining the direction to a target magnetic body from the downhole tool.

The device illustrated in Fig. 18 is a mercury potentiometer sensor, which is in essence a transducer that provides a measurement of the angle of rotation of the tool housing about the longitudinal axis of the housing 102. The device is designed to permit the measurement of this angle irrespective of the borehole inclination. The technique illustrated involves a small ball of mercury 552 disposed for unrestricted movement in a circular, non-metallic race 534. The mercury ball, due to the influence of gravity, will always move along the race seeking the lowest point. The mercury ball contacts a resistive element 534 on one side and contacts a metallic collector ring 556 on the other side. In essence, the mercury is acting in the same manner as the wiper of a potentiometer or variable resistor.

The mercury ball is constrained within the race in order to keep the ball from being broken up by shock and vibration. The ball is surrounded with a low friction material to provide a smooth surface which will not impede the free movement of the ball to the lowest point in the race. The resistive element should have a linear variation in resistance along its entire length to provide a linear response over the entire 360 degree range. In addition, the resistance material used must be physically compatible with the mercury ball in order that a good ohmic contact can be made.

The embodiment illustrated in Fig. 18 includes four contacts that define four quadrants, I, III and IV. Specifically, a positive voltage potential is applied to the resistive element at the zero-degree position. A negative voltage potential is applied to the resistive element, 534 at 180-degree position, and a ground potential is applied to two locations along the resistive element 534 at the 90-degree position and at the 270-degree position.

Fig. 18A is a plot of the output voltage from a collector 556 as a function of the mercury ball position along the race. At the zero-degree position, that is where the apparatus reference plane is vertical and the reference mark of the apparatus is up, the mercury ball 552 will be at the bottom of the race. Consequently, little or no voltage drop will be experienced between the contact 558 and the mercury ball; and therefore, the voltage on the collector output lead 560 will be near the positive voltage supply potential. As the housing rotates counterclockwise, the mercury ball will move along the race in quadrant I. As it moves in this manner, the voltage observed at collector output terminal 560 will decrease linearly until finally, at the 90-degree position the output voltage will be zero volts. If rotation of the housing is continued throughout the full 360 degrees, the output response will be as shown.

Alternatively, the vertical sensor may use only two contacts, that is only two voltage potentials need be attached to the resistive element. Again, a linear resistance as a function of rotation is necessary. It is further necessary that the two contacts be displaced a sufficient distance apart that the mercury ball can pass by the two contact points without shorting them together. By this method, the output voltage would be linear with rotation between, for example, zero degrees and 350 degrees.

Additional approaches to the implementation of the vertical sensor would include a gyroscope disposed in the down hole tool to determine the orientation of the housing with respect to a geographical heading. A gyro benchmark reading would be taken at a known heading at the wellhead with subsequent readings taken throughout the survey related to the benchmark to determine orientation. Also a pendulum which is free to move within the housing could be used. If a pendulum were used, an optical type sensor might be the most advantageous. For example, the suspended mass could have coded apertures through which a light source could project a beam of light onto a photocell behind

the plate. Photocell output would then be representative of the rotational orientation of the tool.

A similar reference sensor could be provided to determine changes in orientation of apparatus 100 by rotation about the X'-axis. A sensor for performing the function of ascertaining housing inclination within the borehole would be placed perpendicular to the vertical reference sensor 152.

2. Surface Instrumentation Apparatus

The surface instrumentation is designed to receive, route and manipulate the data being provided by the sub-surface field sensing apparatus. The surface instrument, in order to be compatible with the multiple sensor output subsurface tool, is a multi-channel instrument. Routing of data within the surface instrumentation is by mode switching and multiplexing. Manipulation of the data is carried out by a programmable calculator receiving multiplexed digital data.

The surface instrumentation includes additional equipment such as power supplies, analog data recorders, and calculator peripheral devices. The peripheral devices could include a printer for supplying an immediate printout and a digital magnetic tape recorder for storing the data and results.

Referring now to Fig. 19, there is shown a block diagram of one embodiment of the surface instrumentation. The receiving portion of the surface instrument comprises a separate signal conditioning amplifier 602, 604, 606, 608 for each data channel. Since data is to be stored and analyzed in a digital programmable calculator, the data must be converted from the analog form in which it is generated downhole into a compatible digital representation. To perform this function, a separate analog-to-digital converter 610, 612, 614, 616 is provided to receive the output of each signal conditional amplifier and digitize it. Programmable calculator 622 is operated with a single data bus, therefore requiring that a digital multiplexer 618 be utilized to route the multi-channel data onto a single data bus to the calculator. An interface 620 is provided to link-up the digital multiplexer 618 and the programmable calculator 622. The interface 620 receives control signals in one format over a control signal bus 624, and on the basis of the calculator input controls to it, the interface provides control signals of a format compatible with the digital multiplexer 618.

In addition to the digitized data from the field sensors, a digital representation of the depth at which each sampling of sensor output was taken is also provided to the multiplexer 618 for routing to programmable calculator 622. Depth indication begins with the reading of a depth indicator shaft on the logging cable unit, which shaft turns a depth indicator 626 that provides a digital representation of the depth of the subsurface tool.

In addition to the digital processing portion of the surface instrumentation, analog signal plotting capability is provided. The analog signal available at the output of each signal conditioning amplifier is applied to a buffer amplifier 628, 630, 632, 634. The buffer amplifiers amplify the signal received to a sufficient level for driving a dual channel strip chart recorder 636. Two multiple position switches 638 and 634 are provided to enable each channel of the strip chart recorders 636 to be connected up to any one of the buffer amplifiers to monitor the data from any one of the field sensors. In addition, the outputs of the signal conditioning amplifiers can be applied to a digital volt meter 642 through a selector switch 644.

When the subsurface field sensing apparatus 100 is being operated in the so-called passive mode, the analog data derived from the D.C. magnetometers are applied directly to their respective signal conditioning amplifiers. However, if the system is being operated in the active mode, the A.C. field sensors are being used, the A.C. signals must be routed first through an AC-to-DC converter or a synchronous detector prior to being applied to the signal conditioning amplifiers. Use of one or the other will depend upon whether it is convenient to run a reference conductor to the surface instruments. Preferably, detectors 650 and 652 are Princeton Applied Research Lock-In Amplifiers, Model 122. Assuming that the circumstances at hand permit, a reference signal is taken from the current source being used to excite the target well. The reference signal is applied to the synchronous detectors to permit phase lock operation. Synchronous detection of the sensor data results in a quasi-static output which is positive for in-phase signals and negative for out-of-phase signals, thereby eliminating ambiguity of direction.

A switching network 660 is provided to permit the routing of the A.C. signals to either AC-to-DC converters 646 and 648 or to synchronous detectors 650 and 652. Switching network 660 comprises two multiple position double pole switches

662 and 664. The incoming A.C. signal is applied to the terminals of switch 662. Then, according to the particular mode of operation the signal of each channel will be applied to the appropriate AC-to-DC converter or synchronous detector. The input leads to the signal conditioning amplifiers 606 and 608 are connected to switch 664. Also, depending upon the mode of operation, switch 644 is positioned to connect each signal conditioning amplifier input to either an AC-to-DC converter or a synchronous detector.

It is noted that because of the limited number of conductors available in the logging cable changes must also be made in the wiring of the subsurface field sensing apparatus in order to connect the A.C. magnetometer sensor circuitry or the electric field probe sensor circuitry to the subsurface tool output connector.

C. SURVEYING APPARATUS OPERATION

In performing target surveying involving the determination of the range and direction to the desired target well from a location along an off-vertical relief well borehole with the above described apparatus of the present invention, it is necessary to first select the passive or active mode of operation. If the first well is not burning, it may be possible to excite the well casing with an alternating electric current to generate a magnetic field about the casing, which would then serve as a magnetic field target for the subsurface field sensing apparatus.

Assuming that the active mode is selected, a cathodic generator, typically a three-phase, full-wave bridge, will be electrically coupled to the well casing, and a ground lead taken to an adjacent well to provide a return path for the current. Since the ripple frequency of the rectified AC is six times the fundamental frequency, the AC field sensing systems in the subsurface tool must have a maximum response at the sixth harmonic of the power generator. Rather than using 360 Hz as the peak response frequency, the AC magnetic field sensor 178 (Fig. 8) and the frequency selective amplifier 176 (Fig. 8) should be tuned to 324 Hz to minimize the interference and false information which may be caused by 60 Hz power systems operating nearby. The reduction of this peak response requires that the power generator governor be regulated to generate 54 Hz rather than 60 Hz. This frequency adjustment is within the range of commonly available generating systems.

If enough current can be driven through the well casing to set up a magnetic field, the AC magnetic field sensor will be used. However, if sufficient current leakage through the casing to ground is being experienced, it may be necessary to use the electric field probes and detect the electric field radially emanating from the surface of the casing.

With the generator exciting the well casing, the subsurface tool is lowered down the borehole being drilled, and a survey is made. Based upon the data provided by the subsurface instrument, the course of the borehole is altered. The direction of drilling is altered until the subsurface field sensing apparatus determines that the borehole is aligned in the direction of the target casing. In the case of the electric field sensor, a maximum voltage gradient will be detected when the electrode sensors are aligned in the direction of the target and when a minimum gradient is detected, the line through the electrodes is perpendicular to the direction of the target. If the AC magnetic sensor is being used, alignment of the sensor axis with the direction of the target will exist when the output of the sensor is at zero.

It is also important to note with regard to Fig. 17 illustrating the surface instrumentation apparatus that in the active mode of operation in order to be able to determine the direction in which the AC sensor is aimed it is necessary to take a signal from the generator exciting the casing and compare it with the signal from the AC sensor. In the event that synchronous detection is used the signal would be applied to the sync reference input 653. If connections are made to provide proper polarities, the sensor output signal will result in a positive output that is in-phase with the reference signal from the generator, then the sensor is pointed toward the target.

In most cases, it will not be possible to excite the casing because of a burning fire at the mouth of the well, which fire can easily spread over a large area. Operation of the survey system under such conditions will have to be performed in the passive mode with the DC magnetometers in the apparatus being used to detect the remanent magnetization of the casing in the target well.

As mentioned previously, in order to orient the apparatus with respect to the surface geographical coordinates, it is necessary to know the field intensity, the

direction with respect to magnetic North, and the dip angle of the earth's field. All of these will be unique values depending upon the exact location on the earth's surface where drilling is to take place.

To begin a survey, the subsurface field sensing apparatus is lowered into the borehole suspended from a seven conductor logging cable secured to the connector at the top of the tool. The apparatus is stopped at a location in the borehole sufficiently far away from the target such that only the earth's field is detected on the magnetic sensors. By measuring the vector components of the earth's magnetic field in the X', Y', Z' coordinate axis system of the apparatus in the manner previously discussed, the slope and azimuth of the borehole can be determined. Thus, the orientation of the tool with respect to the surface drilling unit can also be ascertained.

After the orientation of the borehole has been determined, which orientation does not change radically with distance due to the inability of the drill string to bend at a sharp radius, and the subsurface apparatus has been checked out and determined to be functioning properly, the subsurface instrument is lowered continuously down the borehole. As the instrument is being lowered, measurements of the magnetic field intensity components are made. The surface instrumentation digitizes the measurements and supplies them to the programmable calculator which organizes and analyzes the data. The data may be recorded on magnetic tape for later recall and processing. The processing of data will be in accordance with the equations for ranging outlined previously herein and conventional vector analysis techniques. By performing machine calculations on the data, answers can be displayed on the printer giving the range and direction to the target magnetic source from particular depth locations along the borehole. A print out of data relating this information for each depth location along the borehole provides an indication as to whether the drilling operations are proceeding in a proper direction or will need to be corrected in accordance with the correction equations outlined in the discussion with regard to the diagram of Fig. 5.

As noted in the discussion of making elevation and azimuth correction for the borehole, rotation of the subsurface instrument about its longitudinal axis will affect the readings obtained by the X'-axis and Y'-axis sensors. Practically speaking, the apparatus can rotate without restriction, or it can be partially restricted from free rotation by using standoffs. The standoffs would comprise, for example, four rubber bars equally spaced around the circumference of the housing to restrict rotary motion until the tension in the cable can override the restraining influence of the bars. Rotation of the apparatus will generally not be excessive. However, the problem is greatly diminished by simultaneously sampling and retaining sensor outputs as is performed by the surface instruments.

On the basis of the elevation and azimuth correction angles, the drilling of the relief well is continued along a new path. After drilling has progressed an appropriate distance which is not an extremely large distance with respect to the range of target as determined by the last survey, drilling is interrupted and the subsurface field sensing apparatus may again be lowered into the borehole to make a new survey to determine target range and direction. If a near intercept of the target is made, the borehole may have to be plugged and partially redrilled to place the trajectory of the relief well borehole sufficiently near the target. If redrilling is required, the new trajectory can be planned more accurately, with the new knowledge of the target well position.

Proper operation of the static field sensing system in the subsurface instrument to yield optimum accuracy depends upon precise orientation of the mechanical and magnetic axes of the four DC magnetometer sensor cores. As discussed earlier, each sensor has a cosine response pattern, and a three-dimensional visualization of this pattern would be of a pair of spheres joined together. The axis of maximum sensitivity is a line through the diameter of the spheres and the point of their contact. Also a null axis can be defined in a plane perpendicular to the axis of maximum sensitivity and containing the point of contact of the spheres. Although rotation about the axis of maximum sensitivity theoretically will not affect the sensor response, if the mathematical and magnetic axes do not correspond, then the sensor's axis of maximum sensitivity will define a cone as the sensor is turned about its mechanical axis. Accordingly, variations in the magnetic field being detected will also result. The amount of misalignment of this type can be determined and appropriate correction factors can be applied to the raw data supplied by the sensors.

In addition to the problem of axis misalignment in the individual sensors, there is also the problem of maintaining the sensors at a mutually perpendicular disposition. To correct for this problem, the four sensors should be mechanically aligned as closely as possible, with the misalignment being measured in terms of its response output when placed in precisely defined magnetic fields. Correction factors are also determined for this type of misalignment, which correction factors are applied to the raw data obtained from the subsurface instrument.

A final problem involves adjusting the axial magnetic sensors of the subsurface apparatus to have their magnetic axes coincide with the centerline axis of the cylindrical outer housing. The most convenient solution to this problem is to carefully align the mechanical axis of the axial magnetic sensors with the housing and rely on the correction factor mentioned above that corrects for sensor magnetic axis misalignment with respect to the mechanical axis of the sensor.

Although no techniques have been described in detail for carrying out the calculations for target range and target direction determination, anyone skilled in the computer art can program a computer to solve the equations provided herein and to apply the techniques of vector analysis to the acquired data. Although the calculations may be carried out by a hand-held calculator such as an HP-65, a calculator such as Hewlett-Packard 9815A is preferred. Programs for either instrument may be formulated from the manuals accompanying those instruments.

The foregoing description of the invention has been directed to a particular preferred embodiment of the present invention for purposes of explanation and illustration. It will be apparent, however, to those skilled in this art that many modifications and changes in the apparatus and method may be made without departing from the scope of the invention.

WHAT WE CLAIM IS:—

1. A method of surveying to determine the range from a borehole to a subterranean target exhibiting a magnetic or electric field, comprising measuring the intensity of the magnetic or electric field at a plurality of locations along the length of the borehole to provide signals representative of the intensities at said locations and of the spacing of said locations; utilizing said signals to determine the gradient, in the direction of the borehole, of said field and to provide signals representative of the gradient; and utilizing said signals representative of the intensities and said signals representative of the gradient to determine the range to the target from one of said locations.

2. A method according to claim 1, wherein the measurements of the field intensity are made by two magnetic field sensors spaced apart by a predetermined separation, Δr.

3. A method according to claim 1 or 2, wherein the measurements of the field intensity are made at more than two locations of predetermined separation, Δr, along the axis of the borehole; and the determination of target field intensity gradient is made over each separation between adjacent pairs of locations by forming a ratio $(\Delta H/\Delta r)$ of the difference in adjacent measurements of the field intensity ΔH to the predetermined separation, Δr.

4. A method according to claim 3, wherein the determination of range involves determining an average value of the component of field intensity, H, for each separation using adjacent pairs of measurements; forming ratios

$$\frac{H}{(\Delta H/\Delta r)}$$

of average field intensity component, H, to field intensity gradient, $\Delta H/\Delta r$, in the direction of the axis of the borehole using corresponding measurements for each separation; substituting the ratios

$$\frac{H}{\Delta H/\Delta r}$$

for adjacent separations in the equation

$$\frac{\dfrac{H_1}{\Delta H_1/\Delta r}}{\dfrac{H_2}{\Delta H_2/\Delta r}} = \frac{r_1}{r_2} = \frac{r+(\Delta r/2)}{r+(3\Delta r/2)}$$

where H_1 is the value of H over a first separation, H_2 the value of H over a second, adjacent separation $\Delta H_1/\Delta r$ is the gradient $\Delta H/\Delta r$ over the first separation, $\Delta H_2/\Delta r$ is the gradient $\Delta H/\Delta r$ over the second, adjacent separation, r_1 is the range to the target from the first separation r_2 is the range to the target from the second, adjacent separation; and determining from the equation the value of the range, r.

5. A method according to any one of claims 1 to 4, wherein the measurements of the field intensity are of the intensity components of a static magnetic field in the direction of the axis of the borehole.

6. A method according to claim 5, wherein said field emanates from a ferromagnetic target.

7. A method according to claim 6, wherein said target is a well having remanent magnetism.

8. A method according to claim 5, 6 or 7, further comprising determining the direction to said target from said borehole by measuring the components of the earth's magnetic field along orthogonal axes at a first location in the borehole sufficiently remote from the target to be ineffected by the field of the target; measuring components of the total magnetic field along orthogonal axes at a second location in the borehole sufficiently proximate the target to detect the magnetic field of the target superimposed on the earth's field; and determining the direction of the superimposed magnetic field of the target from the second location using the measurements of the components of the total magnetic field and the measurements of the components of the earth's magnetic field.

9. A method according to claim 8, wherein the determination of the direction to the target involves measuring components of the total magnetic field along three orthoganol axes; subtracting the measured components of the earth's magnetic field along said three orthoganol axes; and resolving the remaining quantities of the components into a resultant vector indicative of the direction to the target.

10. A method according to claim 8 or 9, further comprising determining an azimuth correction angle and an elevation correction angle from the difference in the measured components of the total field at said second location and the measured components of the earth's magnetic field.

11. A method according to any one of claims 1 to 4, wehrein said field is a time-varying magnetic field.

12. A method according to claim 11, further comprising establishing said time-varying magnetic field about a ferromagnetic target.

13 A method according to claim 11 or 12, further comprising orienting a magnetic field sensor to determine the direction perpendicular to the magnetic flux lines of the target; and determining the direction to the target from said direction.

14. A method according to any one of claims 1 to 4, wherein said field is a time varying electric field.

15. A method according to claim 14, further comprising orienting an electric field sensor to determine the direction in which the voltage gradient of the target is a maximum; and determining the direction to the target from said direction.

16. A method according to any one of the preceding claims, further comprising determining the borehole azimuth and inclination.

17. A method according to claim 16, wherein the borehole azimuth and inclination are determined from measurements of the earth's magnetic field and by reference to the dip and direction of the earth's magnetic field.

18. A method of directional subsurface drilling of a borehole to intersect a subterranean target exhibiting a magnetic or electric field, comprising determining the range and direction to the target from the borehole by the method of claim 8, 9, 13 or 15; and orienting the direction of drilling of the borehole in the direction of the target from a position in the borehole from which the target may be conveniently intersected, based upon the target range and direction determinations.

19. A method according to claim 18, further comprising periodically

interrupting drilling; running field sensing apparatus into the borehole and redetermining the range and direction to the target; and adjusting the direction of drilling as appropriate until the borehole intersects the target.

20. A method according to claim 18 or 19, wherein orienting the direction of drilling involves determining an azimuth correction angle and an elevation correction angle.

21. A method according to claim 18, 19 or 20, wherein said borehole is drilled in an off-vertical direction to intersect an existing well.

22. Surveying apparatus for determining the range to a target exhibiting a magnetic or electric field, comprising first and second field sensors spaced apart by a predetermined distance along a reference axis, the sensors either being responsive to a static magnetic field or to an electric field and being arranged with their axes of maximum sensitivity aligned along said reference axis, or the sensors being responsive to a time varying magnetic field and being arranged with the axes of maximum sensitivity perpendicular to said reference axis.

23. Apparatus according to claim 22, wherein said first and second sensors are static magnetic field sensors arranged with their axes of maximum sensitivity aligned with one another.

24. Apparatus according to claim 22 or 23, additionally comprising a pair of magnetic sensors arranged with their axes of maximum sensitivity perpendicular to one another and perpendicular to said reference axis.

25. Apparatus according to claim 24, wherein said pair of magnetic sensors is disposed between said first and second sensors.

26. Apparatus according to claim 23, 24, or 25 wherein each of said magnetic field sensors exhibits a cosine response when rotated about an axis of rotation that is perpendicular to the axis of maximum sensitivity.

27. Apparatus according to any one of claims 23 to 26, wherein each of said magnetic field sensors comprises a magnetic sensor core element; a core driver circuit for providing a driving current to said core element; a detector circuit for receiving an output signal from said core element; a servo-driver circuit coupled to said detector circuit through null balancing means; a feedback line from the output of said servo-driver to said core element, said null balancing means being operable through said feedback line to reduce error in the output of said sensor element; and an output amplifier coupled to the servo-driver circuit.

28. Apparatus according to claim 27, wherein said core driver circuit is adapted to provide a clipped sine wave waveform to said core element.

29. Apparatus according to claim 27 or 28, further comprising an oscillator circuit connected to the core driver circuit of each magnetic field sensor.

30. Apparatus according to claim 29, wherein said core driver circuit comprises an amplifier circuit having an input terminal that is ac coupled to the output terminal of the oscillator circuit, said amplifier having a gain greater than unity; and a push-pull emitter follower current amplifier ac coupled to said amplifier circuit comprising first and second transistors.

31. Apparatus according to any one of claims 27 to 30, wherein said magnetic sensor core element comprises a toroid forming a primary winding; a bobbin of ferromagnetic material having an opening therein for receiving said toroid; and a coil of wire wound about said bobbin to form a secondary winding.

32. Apparatus according to any one of claims 27 to 31, wherein said detector circuit comprises a push-pull emitter follower circuit having first and second transistors; and wherein said null balancing means comprises a potentiometer operably connected to the emitters of said first and second transistors.

33. Apparatus according to any one of claims 29 to 32, wherein said servo-driver circuit comprises an amplifier having first and second input terminals, and an output terminal; first and second transistors arranged in a Darlington amplifier configuration with the base lead of said first transistor being coupled to the output terminal of said amplifier; and a network for setting the gain of said amplifier connecting between the collector of said first transistor and an input terminal of said amplifier; said feedback line connecting to the junction formed by the collector of said first transistor and the emitter of said second transistor and comprising variable resistance means.

34. Apparatus according to any one of claims 27 to 33, wherein said output amplifier comprises a gain potentiometer having a first leg connected to said servo-driver, a second leg connected to a supply of electrical power, and a wiper; an amplifier having a first input lead connected to the wiper of said gain potentiometer, a second input lead and an output terminal; a push-pull emitter

follower circuit connected to the output terminal of said amplifier, comprising first and second transistors; and a network for setting the gain of said amplifier connecting between the junction of the emitters of the transistors and the second input lead of said amplifier.

35. Apparatus according to any one of claims 22 to 34, further comprising a vertical sensor for indicating the degree of rotation of said apparatus about said reference axis.

36. Apparatus according to any one of claims 22 to 35, further comprising a voltage regulator circuit disposed for receiving unregulated power and supplying regulated power to said field sensors.

37. Apparatus according to any one of claims 22 to 36, wherein said field sensors are disposed within a housing of non-magnetic material adapted to be disposed in a borehole.

38. Apparatus according to claim 37, wherein said housing comprises an elongate cylindrical sleeve; a nose cone secured to the forward end of said sleeve; and a multi-conductor connector secured to the rear of said sleeve.

39. Apparatus according to claim 38, wherein said field sensors are mounted on a frame having four elongate stringers extending between said connector and the forward end of said sleeve proximate the nose cone.

40. Apparatus according to any one of claims 22 to 39, further comprising a sensor for detecting a time-varying magnetic field of a predetermined frequency.

41. Apparatus according to claim 40, wherein said sensor for detecting a time-varying magnetic field comprises a parallel inductor and capacitor tuned to provide a maximum flux response when flux lines from said time-varying magnetic field of predetermined frequency coupled to said inductor; and an amplifier coupled to said inductor and capacitor combination for increasing the level of a signal produced by said combination.

42. Apparatus according to any one of claims 22 to 41, further comprising an electric field potential probe for sensing the potential gradient of a time-varying electric field of a predetermined frequency; and a frequency selective amplifier coupled to said electric field potential probe.

43. Apparatus according to any one of claims 22 to 42, further comprising surface instrumentation for receiving signals from said field sensors.

44. Apparatus according to claim 43, wherein said surface instrumentation comprises an analog-to-digital converter for digitizing measurements made by said field sensors; an interface for converting the format of the digitized data; a calculator for receiving the digitized data in converted format and determining at least the range to the target; and display means for presenting at least the range determination.

45. Apparatus according to claim 44, further comprising: a digital multiplexer connected between said analog-to-digital converter and said interface for taking multi channel digital data and placing it onto a single data bus.

46. A method of surveying to determine the range from a borehole to a subterranean target exhibiting a magnetic or electric field, substantially as herein described with reference to the accompanying drawings.

47. A method of directional subsurface drilling of a borehole to intersect a subterranean target exhibiting a magnetic or electric field, substantially as herein described with reference to the accompanying drawings.

48. Surveying apparatus for determining the range to a target exhibiting a magnetic or electric field, substantially as herein described with reference to, and as shown in, the accompanying drawings.

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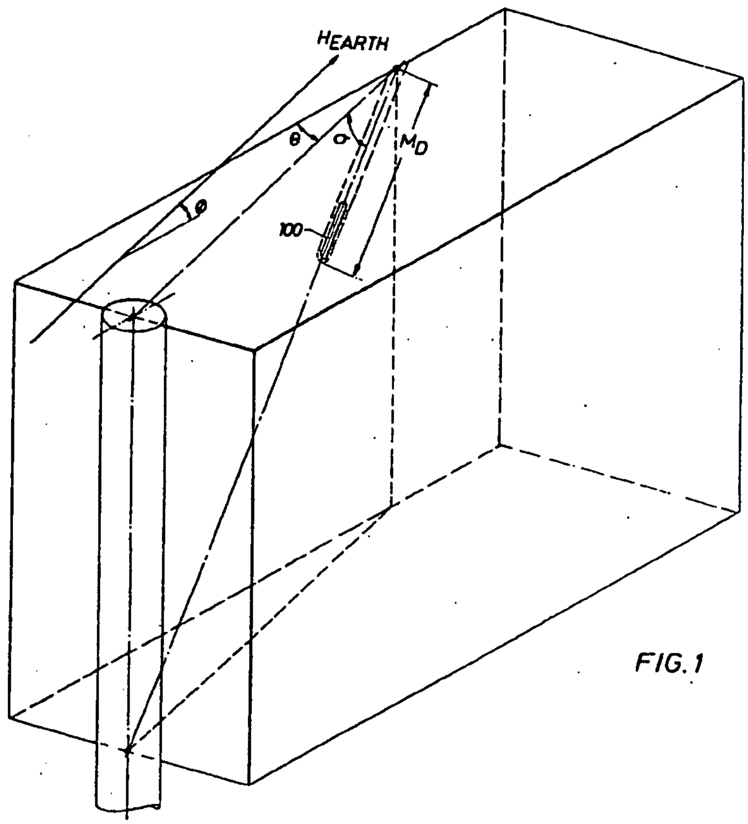

H_{EARTH}
θ
σ
φ
M_D
100

FIG.1

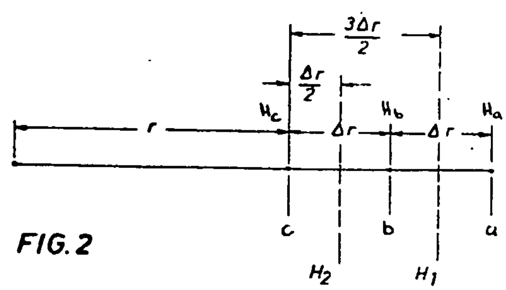
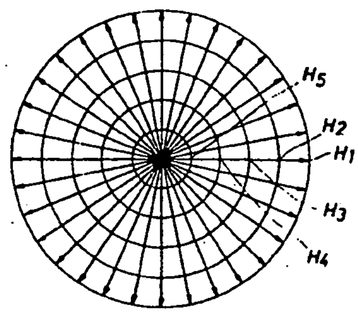

$\frac{3\Delta r}{2}$
$\frac{\Delta r}{2}$
H_c
H_b
H_a
r
Δr
Δr
c
b
a
H_2
H_1

FIG.2

FIG.3



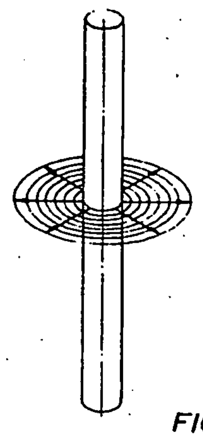


FIG.4

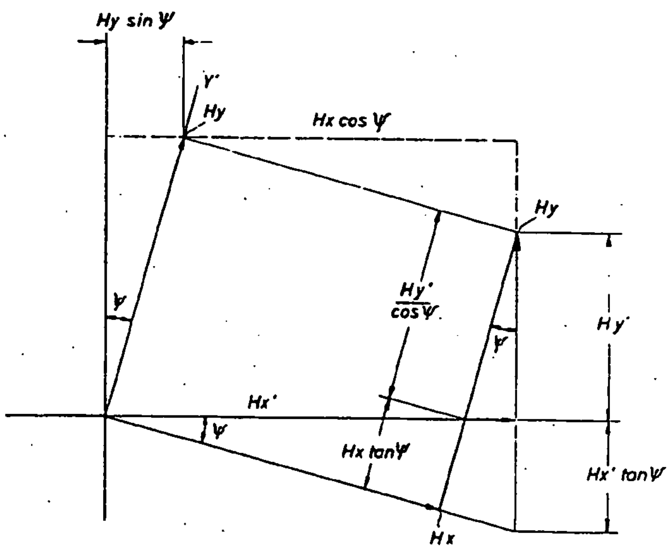


FIG.6

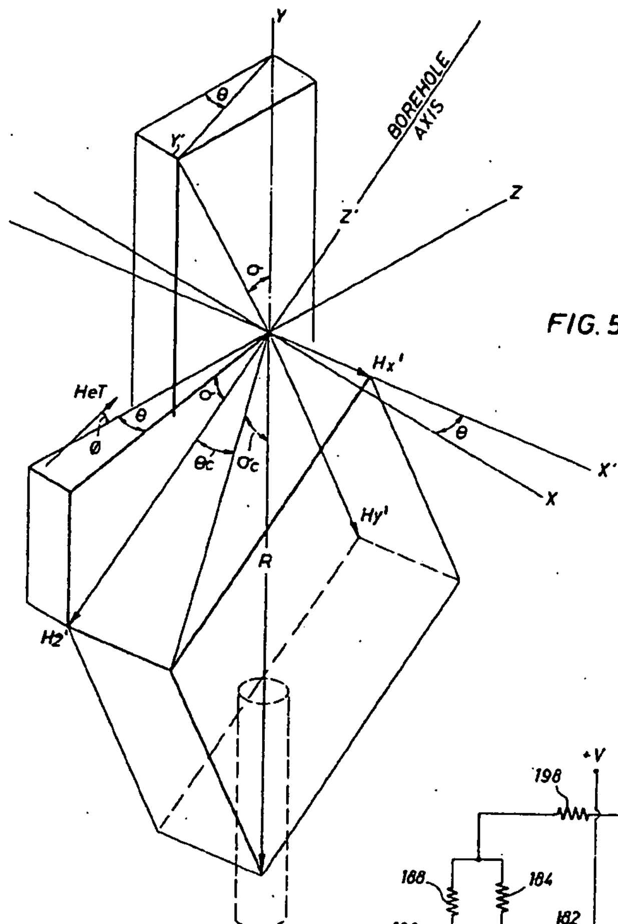

Y
BOREHOLE AXIS
Y'
θ
Z'
Z
σ
HeT
θ
σ
Hx'
φ
θc
σc
θ
X'
X
Hy'
R
H2'

FIG. 5

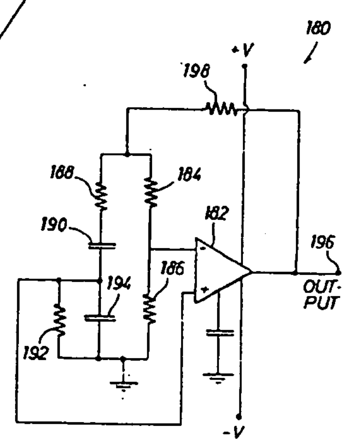

180
+V
198
188
184
182
190
196
186
194
OUT-PUT
192
-V

FIG. 11

FIG. 7A

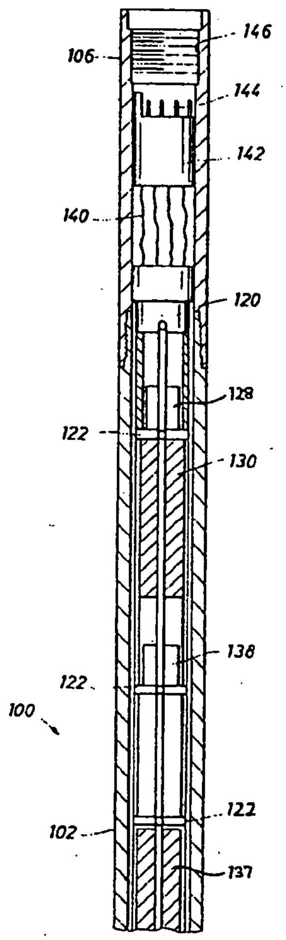
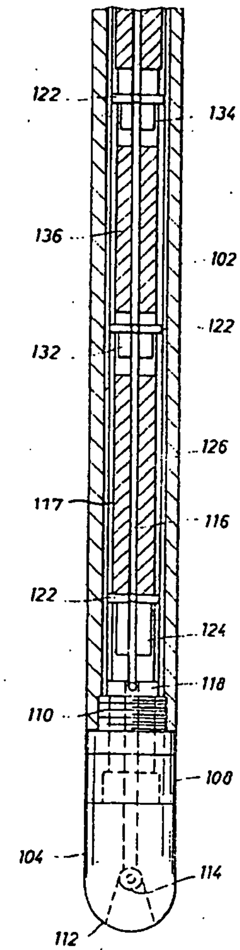

146
106
144
142
140
120
128
122
130
138
122
100
122
102
137

FIG. 7B


122
134
136
102
122
132
126
117
116
122
124
118
110
108
104
114
112

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Sheet 5

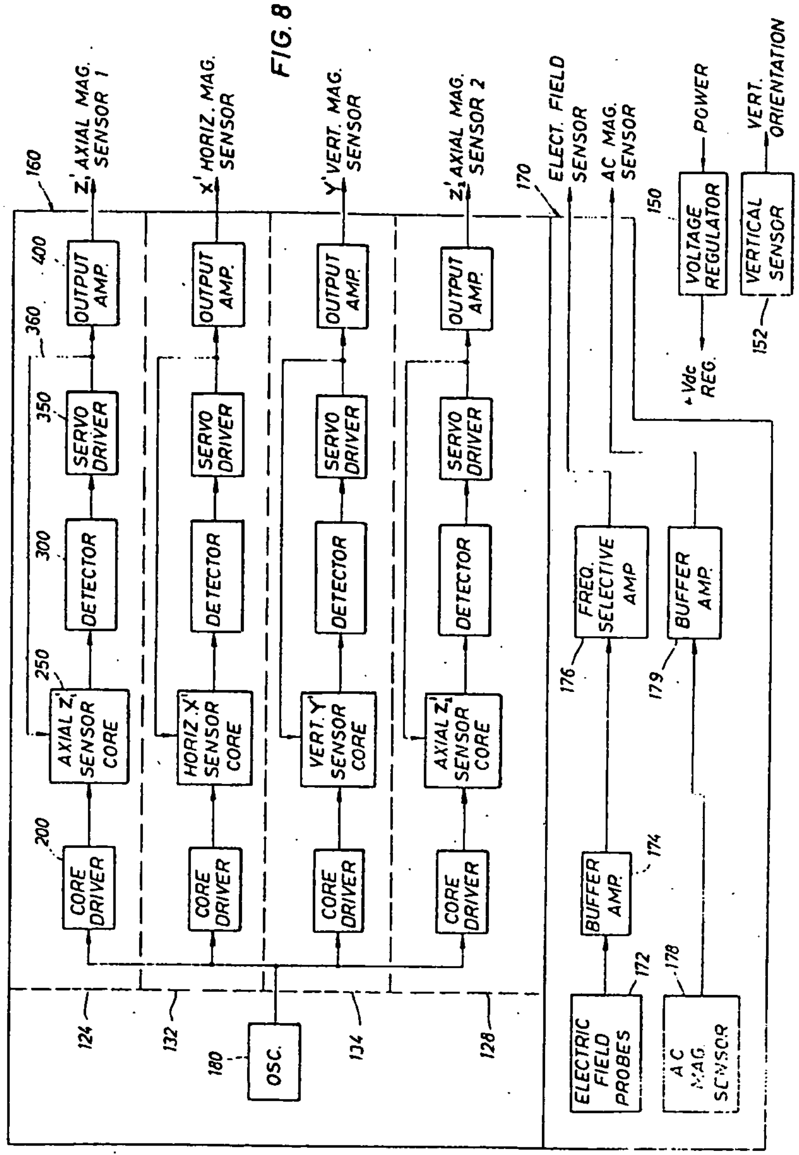
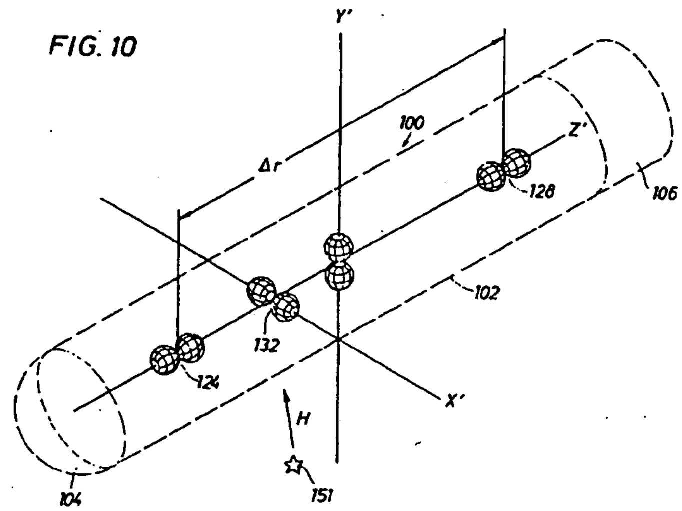


FIG. 8

FIG. 10



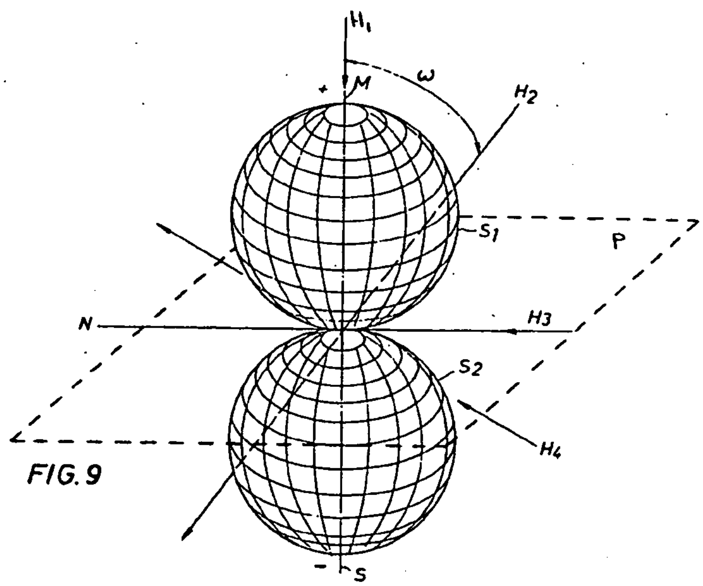


FIG. 9

FIG. 12

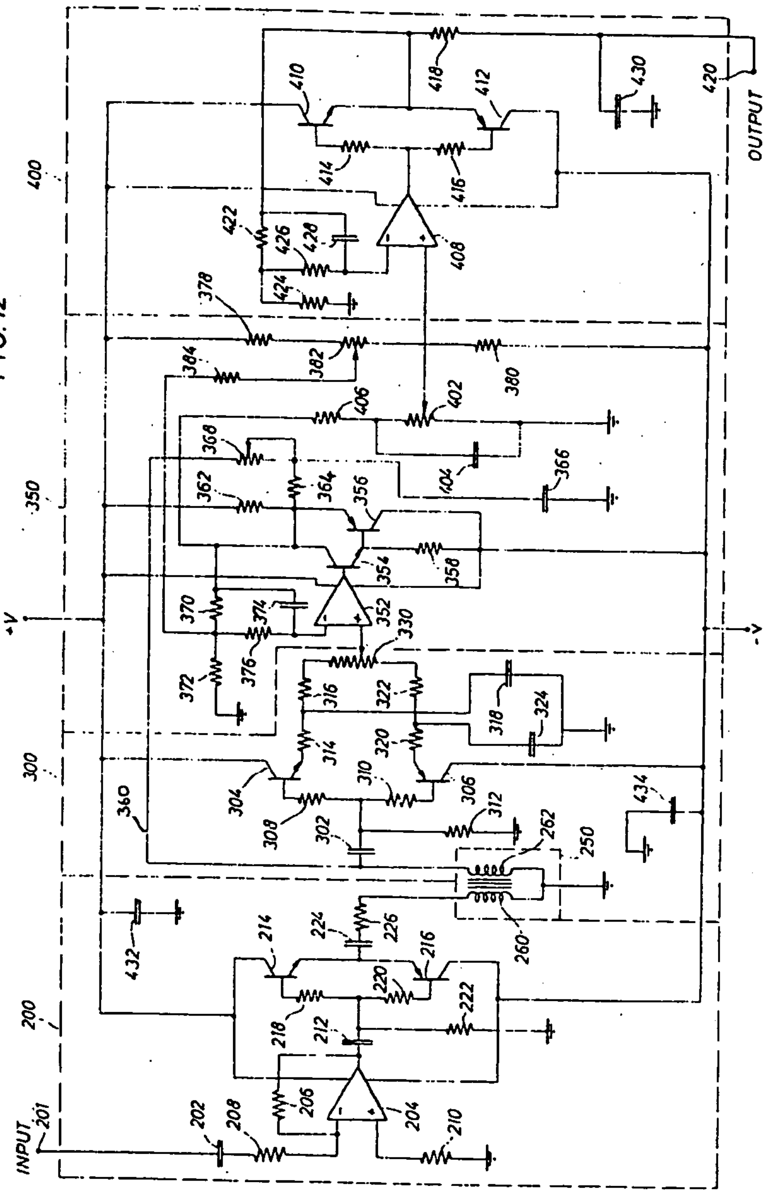


FIG.13

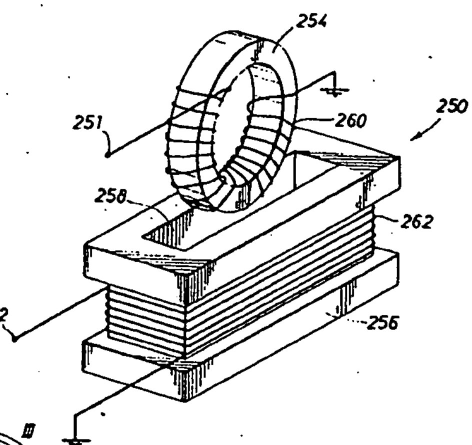


FIG.18

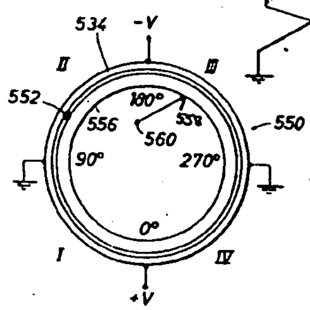
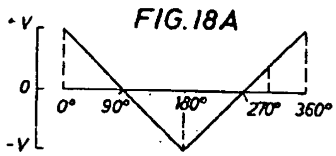


FIG.18A



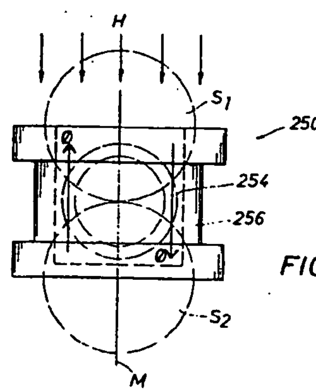


FIG. 14

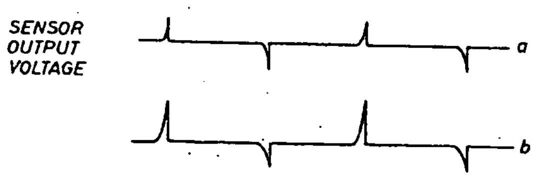


FIG.15

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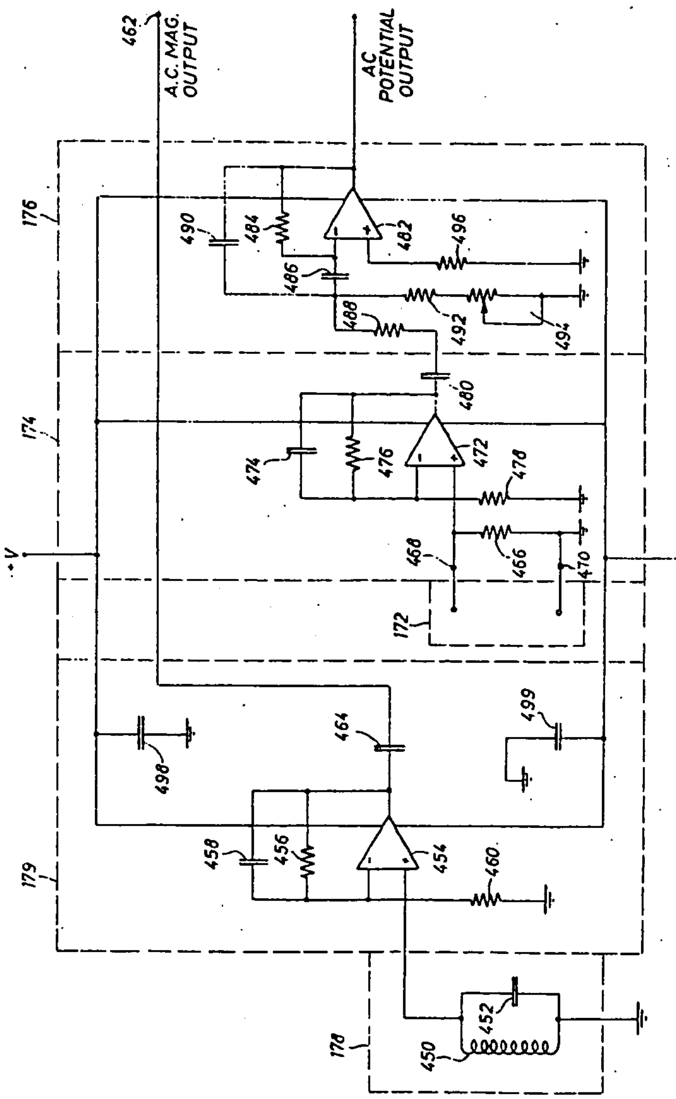

FIG. 16

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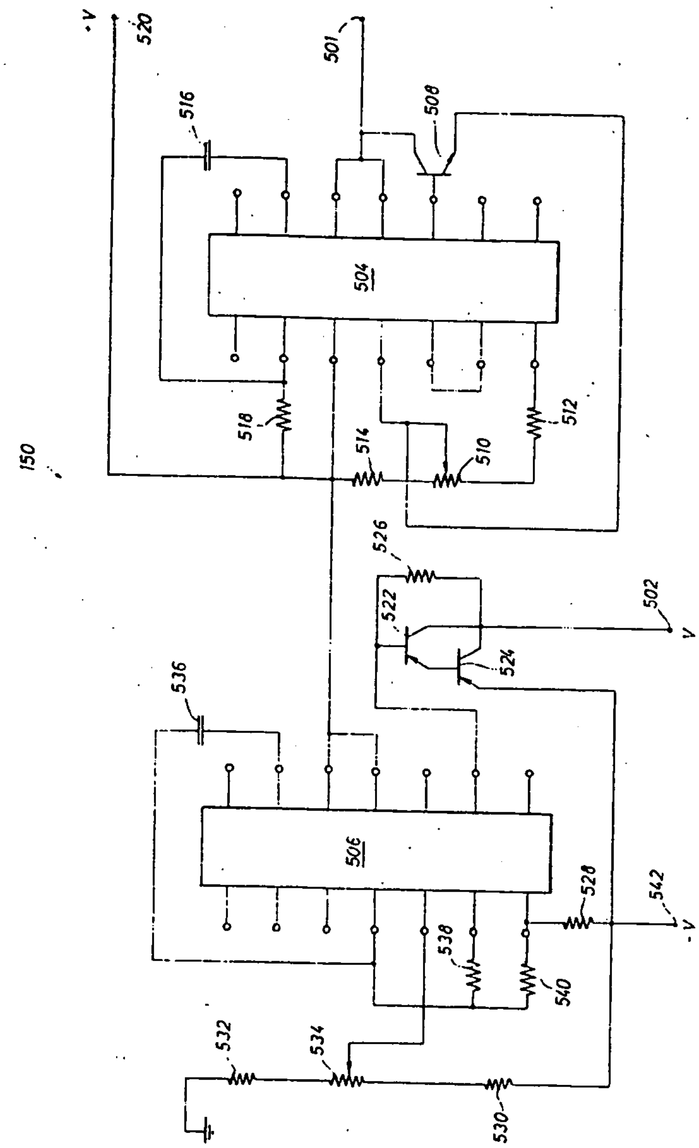

FIG.17

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Sheet 11

FIG. 19